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ARC Stray Light Mitigation

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ARC Stray Light Mitigation

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Section 1

Executive Summary

1.1 Introduction to NIF and ARC

The National Ignition Facility (NIF) is the world's largest and most energetic laser system, located at Lawrence Livermore National Laboratory (LLNL). It is designed to study inertial confinement fusion and to conduct numerous other experiments. [1] NIF has 192 laser beams that are directed at a small targets located at the center of a 5-m radius spherical vacuum chamber.

Currently, four of these 192 beamlines ("one quad") are undergoing modification to achieve peak power exceeding 10^{15} Watts. Though the beams will have about the same energy as other NIF beams, the pulses will be compressed in time to achieve such high peak powers. This new petawatt-class laser, called Advanced Radiographic Capability (ARC), will be the world's highest-energy, ultra-short-pulse laser and will be used to produce x-rays for backlighting NIF experiments. [2] [3]

The 192 laser beams travel about 1.5 km in optical path length down the NIF beamline to the target chamber. It is only in the last few dozen meters, just before entering the target chamber, where the ARC quad is picked-off from the main beamline to enter a compressor vessel to decrease the pulse length and then the parabola vessel to point and focus the light onto the backlighter target (see Figure 1).

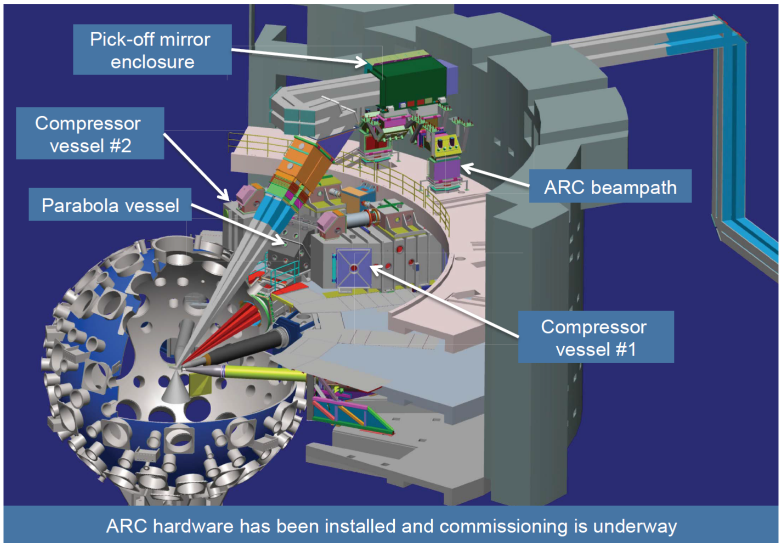

Figure 1: After amplification in the NIF main laser, the four ARC beamlines are compressed in the target bay and focused to Target Chamber Center (TCC). Two Compressor Vessels each compresses two beamlines, while the Parabola Vessel points and focuses all four ARC beamlines to TCC.

1.2 Stray Light Control

High powered lasers are ultimately limited by the power that you can put on each of the optics. High fluence light on an optic can be absorbed or focused by defects in the substrates or coatings, causing damage to the optic. Great care is taken to ensure that the spatial and temporal profiles of the laser pulse do not have any hot spots that can accelerate the wear of the optic. When you reach the limit for power through an individual beamline, then more beamlines need to be added to increase the power further.

Stray light control is a common and necessary task in optical design. Usually, the goal is to decrease unwanted light at the focal plane of an optical system. However, in a high-energy laser, stray light control is necessary for other another reason – that is, high fluence light can cause ablation of materials. Because these ablated particles are contamination that limits optic lifetimes, energy that is not part of the main forward-propagating laser beam must be safely managed. This includes reflections from the forward-propagating laser light and light counter-propagating from the target chamber back down the beamline that may be slightly off-axis.

The mission of the ARC stray light mitigation system is to manage the counter-propagating light from the target chamber down the ARC beamlines. This prevents high fluence light from ablating metals in the beamline, which causes contamination that limits optic lifetimes.

For this project, the system has been defined as simple in that it only has one input (the counter-propagating light) and its only function is to absorb this light with no outputs. The armor glass system is actually a deeply intertwined subsystem of the laser system itself.

The solution will end up being a large collection of passive pieces of absorbing "armor" glass located throughout the beamline. The complexity arises from the physical geometry – the light will enter the beamline apertures with a wide range of characteristics and depending on the initial input angles, require "armor" to be installed in many different places. We will see that schedule and budget constraints will limit the armor from being installed in some areas at that current time, allowing only a partial range of the initial requested capability.

Section 2

Mission Description

2.1 The Advanced Radiographic Capability at the National Ignition Facility

The Advanced Radiographic Capability (ARC) is an upgrade to the National Ignition Facility (NIF) that will provide brighter, more penetrating x-rays to see through the dense core of the laser targets during compression. A pickoff mirror on four of NIF's beamlines allows an optional route to the target chamber center (TCC) through a compressor vessel that decreases the laser's pulse length, and increasing the final power at the target. ARC was conceived in 2002 and most of the optics and supporting hardware have already been manufactured and installed. The design of ARC was based on the physics goals and the space constraints of the NIF target bay.

2.1.1 Optical design of ARC

After amplification in the main laser, each of the four ARC beamlines is picked-off from the usual route to the target chamber by the insertable mirror, called AM1 ("ARC Mirror 1"). Figure 2 shows the location of AM1 in a sketch of one of the NIF main laser beamlines and Figure 3 shows the path from AM1 to the target chamber for two ARC beamlines.

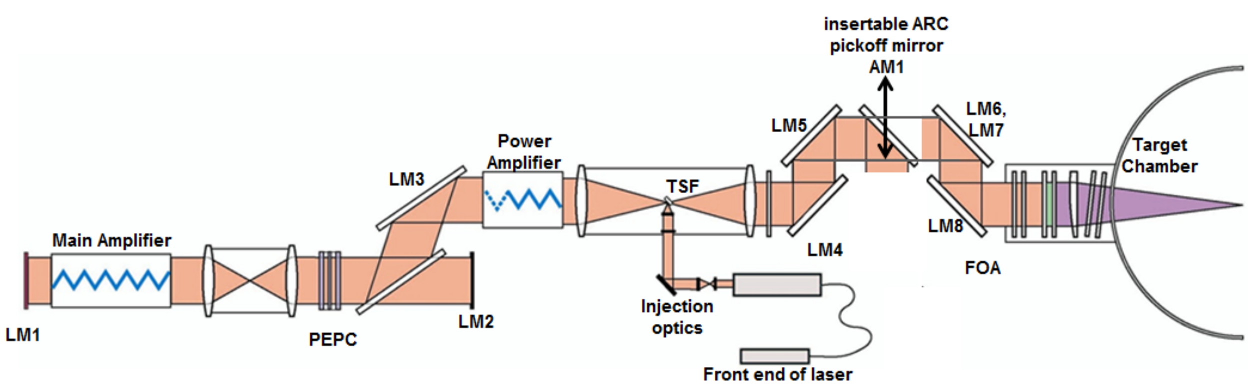

Figure 2: Optical layout sketch of one NIF beamline.

After pickoff at AM1, three mirrors (AM2-AM4) reflect the light through a vacuum window (VW) into a Compressor Vessel (CV). There, four gratings in each beamline (AG1-AG4) in a folded configuration compress the ARC pulse in time. Each of the gratings is divided into two elements, A and B, to limit overall grating size for manufacturability. Thus each of the four beamlines is divided into two "beamlets" (e.g. 353A and 353B). Mirror AM5 reflects the laser into the Parabola Vessel (PV), where mirror AM6 points to a parabolic mirror, AM7, used to focus the previously collimated light. A final mirror, called AM8, is actuated to point and center the beamlets to different backlighter locations. These backlighters emit the intense x-rays used for creating radiographs of the imploding NIF targets. As the laser is traveling to the backlighters, it passes through one final optic, the disposable debris shield (DDS), which is a frequently-replaced, sacrificial window isolating the parabola vessel from the contamination inside the target chamber. (Appendix A defines acronyms and other commonly used terms throughout this project, and is provided for reference.)

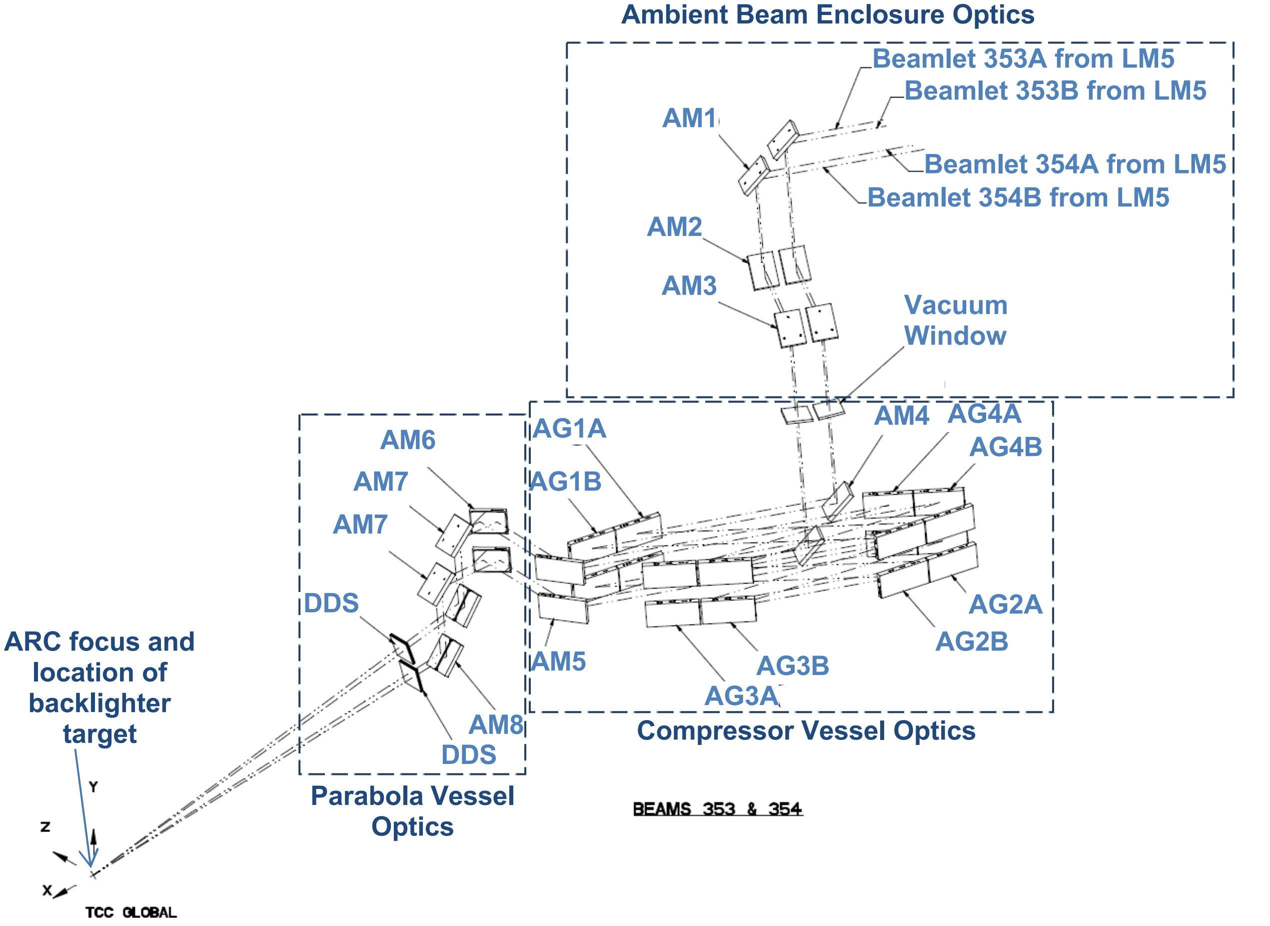

Figure 3: ARC optical layout for Beamlines 353 and 354. All of the optics shown here need to be protected by the ARC stray light mitigation system.

2.2 The threat of high fluence light on optics lifetimes

The peak fluence (power density) on an optic in a high energy laser is incredibly high and can cause "wear" on the optics. Transmissive optics (e.g. lenses) must be made with pure glass, with minimal bubbles, cracks, inclusions and subsurface damage sites, which can absorb or focus laser light, causing damage under intense under laser illumination. Additionally, both the anti-reflective (AR) coatings for the transmissive optics and high reflective coatings for the mirrors need to be made to be extremely defect-free to limit potential damage growth sites (like the example shown in Figure 4). The risk of damage to optics through this mechanism is what ultimately constrains the total energy in the laser.

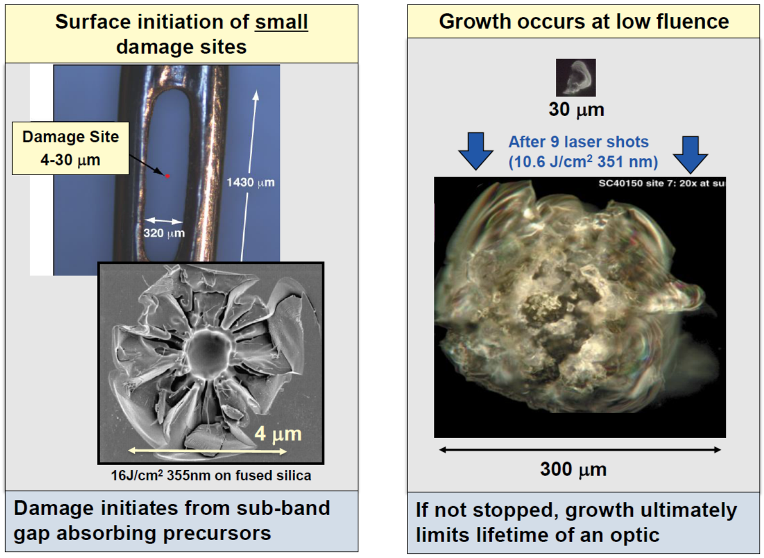

Figure 4: Laser-induced optical damage is an important design constraint for high fluence laser systems. [Spaeth/Suratwala/Parham]

If the installation environment (e.g. beam tube or vacuum chamber) is unclean or becomes so from ablated particles, then those can initiate damage as well, if they land on the optics. As a result, much effort goes into the design of NIF optics and cleanliness protocols to increase the lifetimes of the optics as long as possible. When there is a damage site on an optic, it grows increasingly faster when exposed to high-powered laser light, so there are multiple systems on NIF to measure these sites in situ and another system that can modulate the beam's profile to block light in those areas. When there are too many damage sites on an optic, it needs to be replaced. Some of the final optics, which wear more quickly than optics in the main laser, are taken out of the beamline and refurbished in the on-site optics recycle loop (Optics Mitigation Facility). The on-site optics recycle loop handles the final transmissive NIF "3w" optics, but would not be able to refurbish the specialized ARC gratings or mirrors.

2.3 The mission description: protect the ARC beamlines from high fluence light

NIF is an incredibly complicated system, with layers upon layers of subsystems. Some of the subsystems that work together on NIF and ARC to increase optic lifetimes were described in Section 2.2. In order to extend optic lifetimes, the environment for the optics needs to be as clean as possible and a combination of techniques is used in support of that goal. For example, the beam is enclosed in sealed beam tubes with positive pressure of argon and vacuum chambers in various parts of its travel. There is a disposable debris shield isolating the parabola vessel from the target chamber, and an AM8 "air knife" is installed to blow a puff of "air" across the optics to blow away particles.

Figure 5 shows ARC stray light mitigation system as a subsystem that helps maintain cleanliness for NIF and ARC, where the system to maintain cleanliness is a subsystem is the system that maximizes optic lifetimes, which itself is still a subsystem within the overall laser.

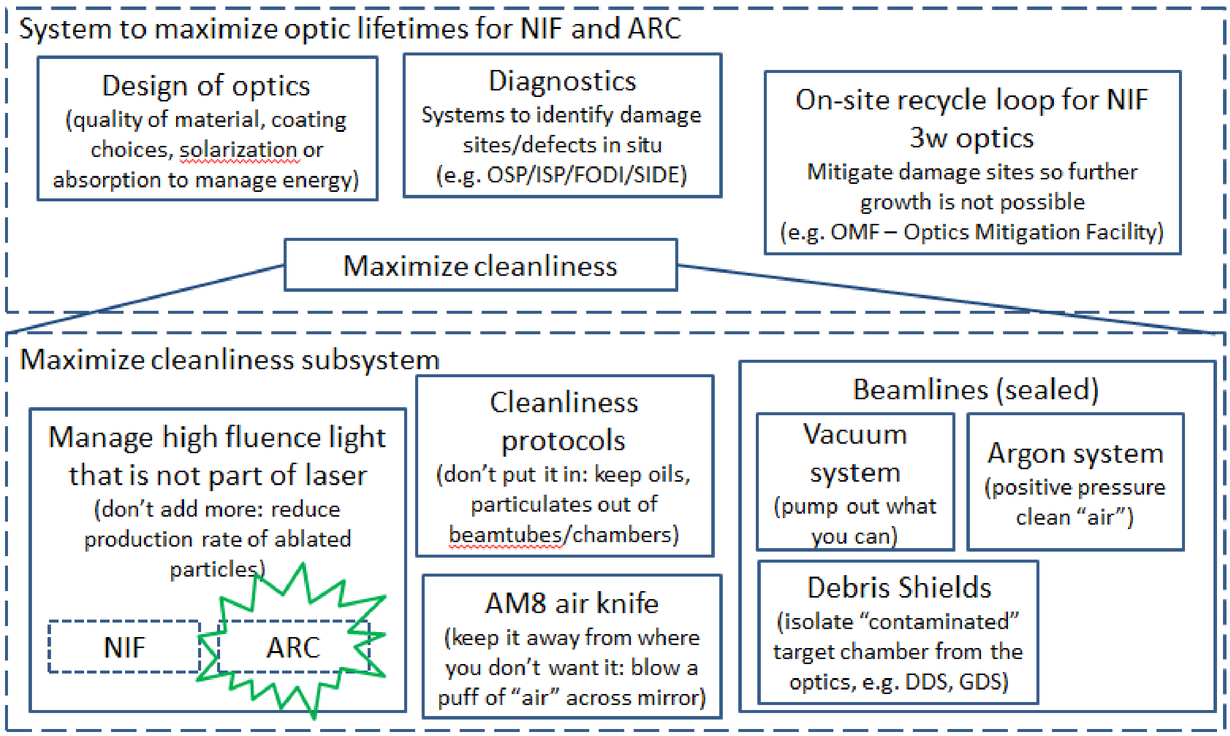

Figure 5: The system chosen for this project (ARC stray light mitigation, shown with the green star outline) is a subsystem in the system that maximizes beamline cleanliness, which itself is a subsystem in the system that maximizes optic lifetimes.

2.4 System Context Diagram

The system context diagram for the ARC stray light mitigation system (with dotted blue outline is shown in Figure 6. (This is the subsystem shown in the green star outline in Figure 5.) The ARC stray light mitigation system needs to manage high fluence light threatening the system from sources that may originate in the front-end of the laser (e.g. unwanted reflections from the forward propagating beam) or that may originate from the target chamber (e.g. counter-propagating sources).

The mission of the ARC stray light mitigation system is to manage the counter-propagating light from the target chamber down the ARC beamlines. This prevents high fluence light from ablating metals in the beamline, which causes contamination that limits optic lifetimes.

Mitigation for stray reflections and diffraction orders from the forward-propagating (FP) laser has already been considered and absorbing glass has been placed in the beamlines to absorb this light. Identifying the counter-propagating (CP) threats from the light exiting the target chamber and going back down the beamlines for the first two beamlines to be commissioned (B353 and B354) and protecting from these threats is the current scope. Beamlines B351 and B352 are not yet fully populated with optics and the entrance apertures to the beamlines will be blanked off with stainless steel plates. It is anticipated that information learned and techniques used for the first two beamlines will help that future effort.

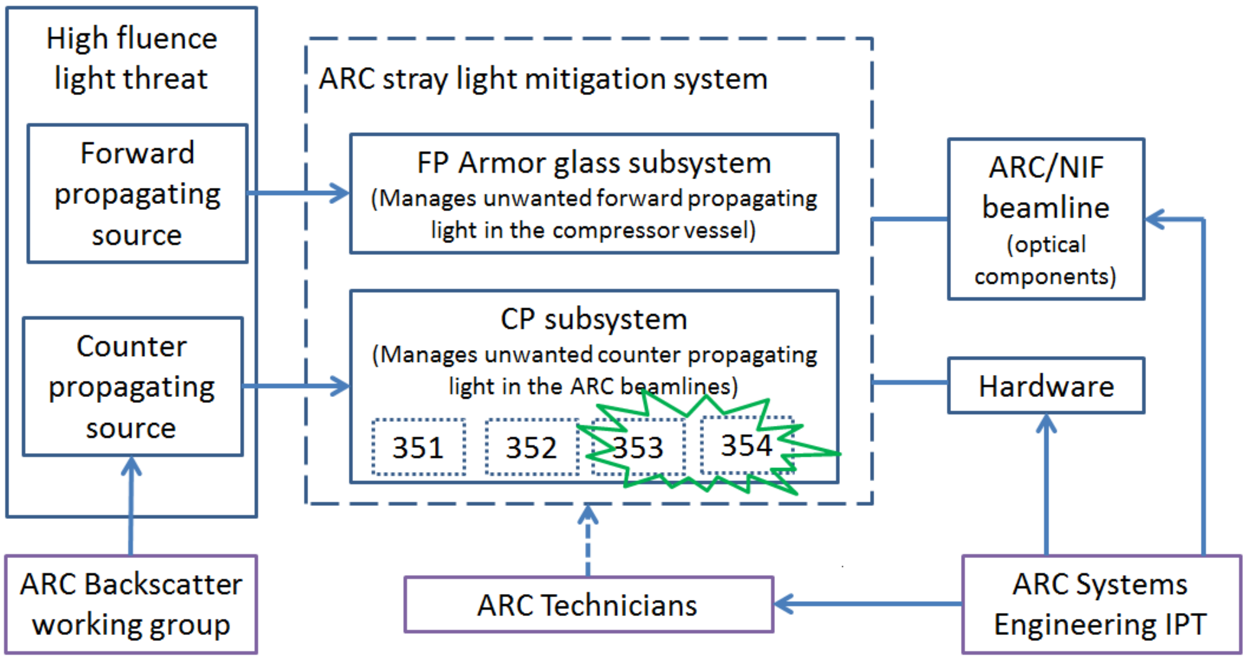

Figure 6: System context diagram for the ARC stray light mitigation system. Active stakeholders that interact with this system while the laser is operating are the high fluence light threat and the ARC optical components and hardware that require protection. The boxes shown in purple represent people. The key stakeholders (ARC backscatter working group and ARC Systems engineering integrated project team) are the people that are responsible for the system, but in this diagram, do not link directly to the system. The technicians who install/maintain the system are the only passive stakeholder shown in this diagram. Finally, the scope of the current work is shown with a green star outline (beamlines 353 and 354) for counter-propagating light.

2.5 Stakeholders

2.5.1 Active Stakeholders

As the NIF and ARC systems are high energy lasers, due to danger, people do not directly interact with the laser, during a shot, except to initiate it from the control room. If active stakeholders are those that interact with the system during operation, none of them would be human. For this system, the key stakeholders are the people responsible for the non-human active stakeholders and will also be listed as active stakeholders.

2.5.1.1 Counter-propagating light source (the threat)

The first active stakeholder is the light counter-propagating (CP) down the ARC beamline. This light is generated inside the target chamber where the forward-propagating laser hits the backlighter target and generates a plasma. Some of the laser light will be scattered in many directions from this plasma, including back into the ARC beamline. (It is this active stakeholder that generates the system capability needed of protecting the beamline.) The system must be capable of mitigating this light (with its given wavelength, fluence, polarization and direction of travel). The backscatter working group is the key stakeholder representing this light.

2.5.1.2 Backscatter working group

Representatives of this team of NIF and ARC scientists and engineers actively participated in the many ARC stray light system meetings and acted as the voice for the counter-propagating light threat listed above. The CP light source, as an active stakeholder cannot be interviewed during the design phase, and some of the estimates of its characteristics are just that – estimates. (Note: the uncertainty is in the energy levels and angular spread at the source inside the target chamber. Optical models can predict how this light will propagate down the beamline once it enters.)

2.5.1.3 ARC and NIF optical components

The ARC and NIF optical components propagate light down the beamlines and are also what the system is designed to protect. Protecting the optical components in the beamline from damage is the highest priority. This is done by keeping the beam tubes and the vessels holding optical components clean from particulates. Cleanliness is maintained by ensuring that the counter-propagating light threat above does not ablate metal particles from the next active stakeholder, the ARC and NIF mounting hardware.

In reality, the ARC stray light mitigation system and laser system, including the components described as an active stakeholder here, are deeply intertwined as a large complex system because they function together, but for the purposes of this project, this seems to be the way to break it down into something manageable.

2.5.1.4 ARC and NIF mounting hardware

The ARC and NIF mounting hardware hold the optics in place in the laser. As these components hold the optics in place, they come very close to the laser light itself. If any high fluence light strays outside the aperture of the optic, this is likely what the light will hit. These components are made primarily out of metal, which can be a source of ablated particles in the beamline. Causing damage to the material itself is not a primary concern for metal, though it can be for other materials, such as polymers (e.g. cabling, gaskets, PEEK washers). (If the high fluence light was expected to burn a hole in the wall, then this would be a concern, but at these wavelength/energy levels, the most we might see a scorch mark.)

2.5.1.5 ARC Systems Engineering Integrated Project Team (IPT) – key stakeholder

The team of ARC scientists and engineers were active participants in the many ARC stray light system meetings and includes the ARC system manager, responsible for the operation of the hardware listed above. In meetings, they also represented the technicians that directly interact with the hardware, identified next.

Key Expectation (Capability)	Why
High fluence light will not illuminate metal hardware.	Do not want to ablate particle that can initiate damage in the optics.
High fluence light will not illuminate polymers.	Do not want to damage polymer material.

2.5.2 Passive Stakeholders

Passive stakeholders may impose constraints on a system, but do not otherwise interact with it. Here I include the technicians that do interact with the hardware of the system physically, but since they do not interact with the system during operation, I'll define them to be passive, not active stakeholders.

2.5.2.1 DOE/Congress/Taxpayers

The first group of passive stakeholders is the people and funding agencies for NIF and ARC. These people include the Department of Energy (DOE), Congress, and taxpayers and they want to see that their money is well spent.

2.5.2.2 NIF management

The second passive stakeholder is NIF management. This group of laboratory employees manages all of schedules and budgets throughout the NIF system (including ARC). The schedule constraints require the stray light mitigation system to be installed for during a facility maintenance period that was planned in late October/early November 2014 so the system would be available for ARC commissioning in 2015. Although there is budget for the system, I do not have the figures to include here.

Finally, this stakeholder wants NIF to be seen as successful in the science world and does not want to see their organization's image be tarnished by unsuccessful missions or by damaging equipment due to insufficient protection. (This would be true for all LLNL and NIF employees as well.)

2.5.2.3 ARC users

The third group of passive stakeholders is the users of ARC. This may include the physicists and other engineers (e.g. alignment) who expect to be able to use ARC for collecting data in their experiments. They expect that the ARC stray light mitigation system will be available 24-7 and that it will not require any special maintenance, inputs or attention on their part and that the laser itself is available for shots or that it is able to operate at the desired energy or peak power levels once commissioned (i.e. the optics have not been damaged).

They could be considered active stakeholders for the ARC system, but as they do not directly interact with the ARC stray light mitigation system, they are passive users here. Finally, they expect that their backlighters may be allowed to be located anywhere inside the "ARC pointing volume," though they do not necessarily have experiments planned that require this. Finally, those backlighter experiments designs influence the properties of the counter-propagating light threat itself.

2.5.2.4 NIF users

The fourth group of passive stakeholders is the users of NIF. This may include the NIF shot director, physicists and other engineers who expect to be able to use NIF for experiments that do not require the use of ARC. They do not want to see that the NIF beamlines (before the ARC pickoff) are unavailable because of damage from the ARC counter-propagating light, however, they also would not like the beamlines to be unavailable during installation of the stray light mitigation solution. Note – these could be conflicting requirements! There are periods of time for facility maintenance when there are not shots planned, so this could lead to scheduling constraints.

2.5.2.5 Optics team

The optics team is group of the people responsible for designing, manufacturing, and procuring the optics. They made choices for substrate materials and coatings early in the design but are not part of the operation of ARC. They impose the constraint of maintaining cleanliness with the expectation that the optics will be protected and treated carefully during operation to ensure lifetimes are not needlessly shortened. This team has not been part of regular discussions for the ARC CP stray light design, however, they have the experts on and have studied in detail the likely damage rates on optics (depending on surface damage, or contamination/particulate models, ablation rates of materials, and transport models of ablated particles).

2.5.2.6 Cleanliness Steering Committee

The next passive stakeholder is the Cleanliness Steering Committee. This team manages the particulate levels in the NIF and ARC beamlines before and during operation. They determine cleaning protocols for hardware [4] before installation or which materials are allowed for example. Though a constraint has not allocated for an acceptable contamination rate due to counter-propagating laser light ablating material in

ARC, this ultimately led to the key acceptance criteria that ARC CP stray light mitigation system must limit the fluence on all surfaces to be less than the measured laser damage threshold of the material.

2.5.2.7 Provider of mitigation techniques (solution-dependent)

The next passive stakeholders are the provider of the solutions for the ARC CP stray light mitigation. They may impose constraints, based on specific aspects of the characteristics the solution they can provide. The ultimate solution to chosen protect against the counter-propagating light threat will be found later in this report includes "armor glass" and temporarily limiting the previously-defined ARC volume for shots until complete mitigation is provided/installed. Thus the additional stakeholders include armor glass manufacturers and the TaLIS team that implements the control of currently allowed pointing (TaLIS: target and laser interaction).

2.5.2.8 ARC technicians

The final active stakeholders are the technicians who need to install and maintain any equipment for the stray light mitigation system. These technicians are also responsible for ARC beamline optics installation and maintenance. They interact with the hardware, but not while the system is operational, so they are not defined as active stakeholders. They impose constraints on the physical system characteristics because they have the desire not to damage either themselves or hardware during installation and maintenance.

Expectation	Why
Reasonable size/weight restrictions for hardware or crane availability. Access to area where hardware needs to be installed. Storage facilities when not in use.	Hardware can be handled without damage to it, the main ARC beamline components, or the operator.

2.6 Sacred Expectations

The ARC stray light mitigation system could be considered a subsystem for the system whose sacred expectation is to maintain cleanliness in the beamlines. The system to maintain cleanliness could be considered a subsystem in the system whose sacred expectation is to maximize the lifetimes of the optical components, as shown in Figure 7. This could be considered a subsystem of the laser itself, which has the sacred expectation to provide the highest peak energy or power possible (while maintaining some required beam spatial and temporal specifications).

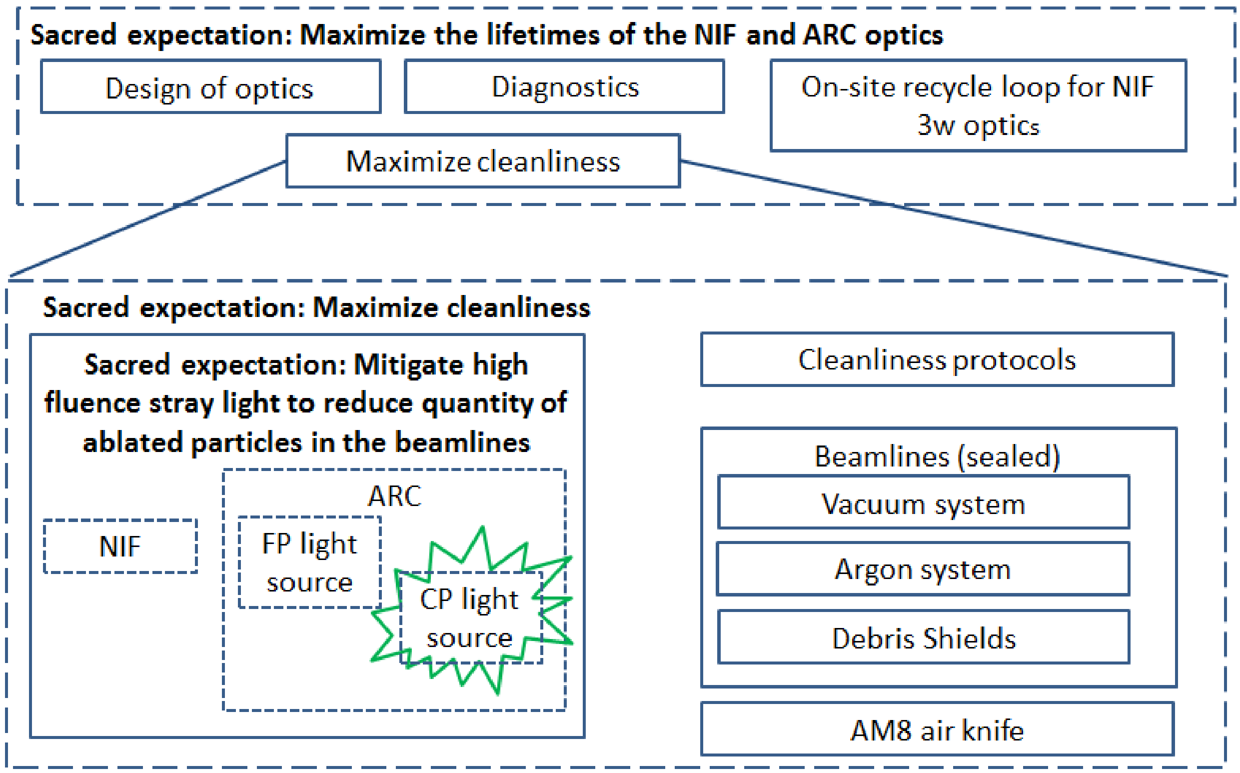

Figure 7: The ARC Counter propagating (CP) Stray Light mitigation system is nested within other systems that aim to reach higher level goals of maintaining cleanliness to achieve increased optic lifetimes.

The sacred expectations are those developed from the active stakeholders. Basically, together they ensure ARC will not self-destruct in order to operate as intended.

2.6.1 Sacred Expectation 1: Minimize ablation to reduce probability of optics damage

High fluence light counter propagating down the ARC beamline will be mitigated to minimize ablation of particulates in the beamlines that can cause damage should they land on the optics and are subsequently illuminated by the laser.

2.6.2 Sacred Expectation 2: Shall not impede operation of ARC or NIF

Any mitigation solutions shall not impede normal operation of ARC or NIF. For example, any hardware added shall not block the main forward-propagating beam (which could limit the peak power and the beam uniformity).

2.7 Key stakeholder acceptance criteria

The key acceptance criterion is that *the expected fluence on each surface after mitigation by this system is less than the associated damage threshold of that material*. The details of what “expected fluence” and “damage threshold” means throughout are discussed in Section 4, “System Drivers and Constraints.”

Section 3

System Operational Context and Reference Operational Architecture

In Section 3, the reference operational architecture used for NIF is discussed in Section 3.1, the difference between the NIF final optics and ARC are discussed in Section 3.2 and the system boundary is described in Section 3.3.

3.1 NIF Stray Light Protection

The NIF laser itself provides the initial reference architecture for the implementation of stray light control. It is a very similar system, as the ARC beamlines are physically connected to NIF itself. The goal of increasing lifetimes of optics is exactly the same, as are the physics behind the threats causing the optics damage. The same methods used to accomplish that goal, including the design of flawless optics, installed in, and operated in a very clean environment. A combination of techniques were employed to manage stray light in the NIF the main laser [5] and Final Optics Assemblies (see Figure 8) and keep the environment free of ablated particles, including "armor" glass to absorb ghost reflections, beam dumps to manage energetic foci and stainless steel shielding to protect polymers and cables.

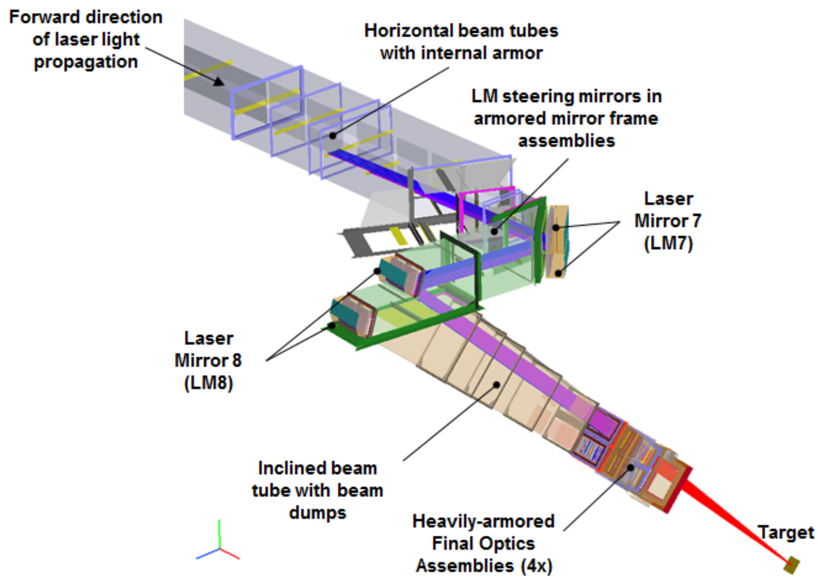

Figure 8: The end of the one quad of NIF beamlines, leading into the Final Optics Assemblies and the Target.

In particular, the mitigation techniques used in the final optics for NIF provides the reference architecture that most closely matches that required for ARC. This makes sense, as the part of ARC we need to protect is a replacement for this part of NIF. While early beamline designs for the NIF final optics used highly tilted optics to reflect unwanted light to absorbers on the walls, the current design uses low-angle optics with many absorbing glass "picture frames" that scrape unwanted stray light from the system (see Figure 9).

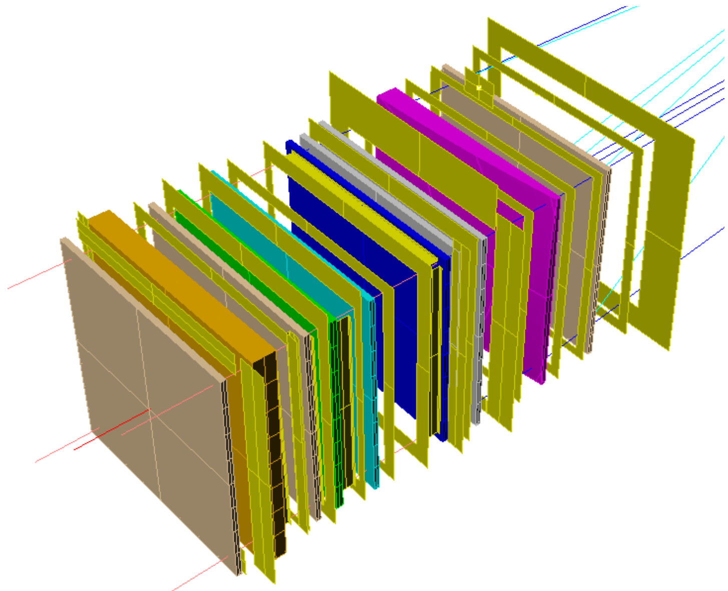

Figure 9: The Final Optics Assembly for one NIF beamline includes approximately 40 pieces of armor glass (shown in mustard yellow). Armor "picture frames" scrape off ghost light paths exiting the beam aperture before the light can intercept metal hardware.

The "armor" glass absorbs light as it passes through the glass according to Beer's Law (exponential law that gives fraction of energy transmitted as a function of attenuation coefficient and thickness of material). The glass that is used for NIF is ideal because the attenuation coefficient allows the majority of the light to be absorbed through the bulk of the material. (i.e. If the attenuation coefficient were higher, then the majority of the light would be absorbed in the surface layer of the glass, which could damage the glass, or if the attenuation was less, then if the thickness is not sufficient, the light might transmit through the material completely and not provide any of the functionality we desire.) Super Grey, manufactured by Pilkington, is the glass used for NIF. It is an architectural glass, typically used for buildings, so it is available in large sizes and bulk quantities.

3.2 Difference between NIF and ARC

The major difference between the NIF and ARC beamlines is that while NIF converts the 1w (1053nm) light to 3w (351nm) before focusing with lenses onto a target (see Figure 10), ARC light remains the same wavelength (1w, or 1053nm) all the way to the target. Essentially, the NIF laser has an optical isolator for counter-propagating light, while the ARC beamlines do not. This makes the ARC CP stray light mitigation much more challenging to design.

The light counter-propagating back into the NIF beamline does not have the correct optical properties for any more frequency conversion (wavelength changes). The 3w light that reflects from the target back into the beamline cannot propagate through the system because the mirror coatings are designed to not be reflective at this wavelength. Only small amounts 1w and 2w light enter the beamline due to the geometry at the target chamber – this light is not focused to the target and doesn't reflect from it.

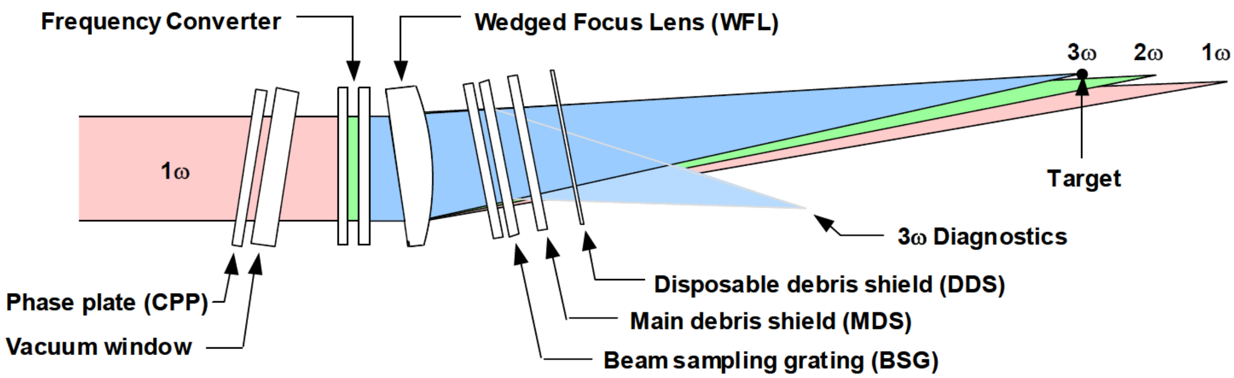

Figure 10: Schematic of the optical configuration of the NIF FOA [6].

3.3 System Boundary

The system boundary here is defined by what is being protected and how it is being protected. First, I'll define the physical area of the beamlines requiring protection and second by the available method(s) used for protection.

3.3.1 Protecting what?

This system is the ARC stray light mitigation system, designed to protect the ARC beamlines (beams 351, 352, 353 and 354) to the TSF pinholes, as shown in Figure 11. It *does not* include or consider any ARC light threats that might counter-propagate into any of the other (NIF-only) beamlines, which will be controlled by backlighter and laser geometry. The areas of ARC beamlines that need protection from stray light can be summarized as the 1) parabola vessel, 2) the compressor vessels, 3) the Ambient Beam Enclosure (ABE) and 4) the 351-354 NIF optics from LM5 to the TSF pinholes. (Refer back to Figure 2 and Figure 3 if needed.)

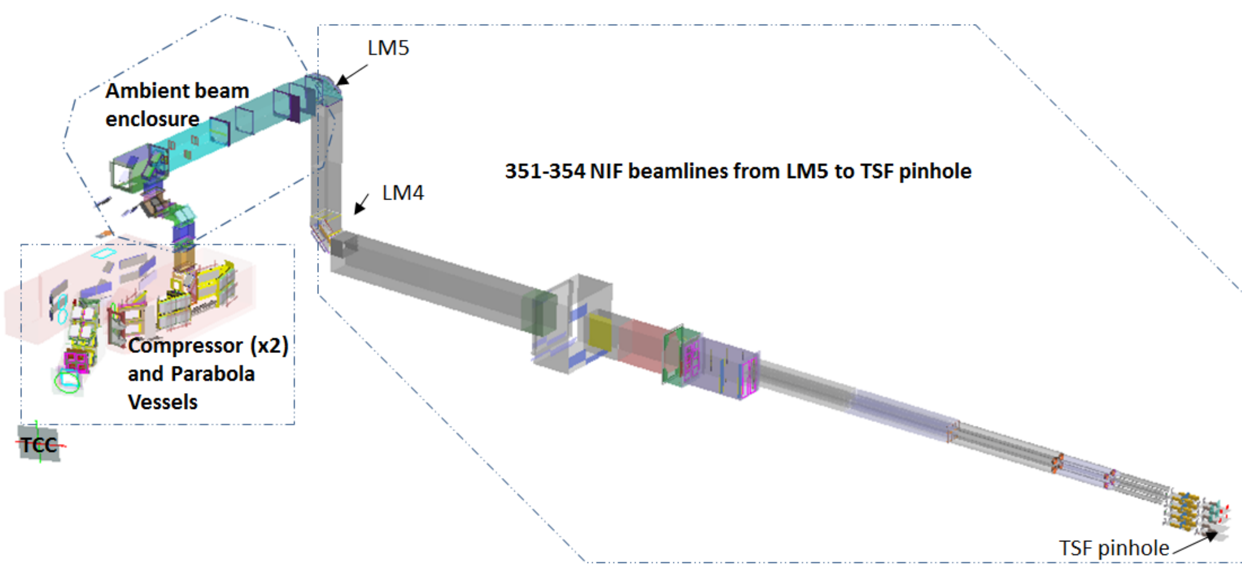

Figure 11: ARC beamlines through CV2 as modeled in FRED.

Any counter-propagating light that passes through the pinhole will have small enough angular extent to propagate down the beamline without exiting the apertures of the optics and illuminating any hardware in the beamline. This light is eventually stopped from reaching the very front-end of the laser by an optical switch, called the Plasma Electrode Pockels Cell (PEPC).

3.3.2 General methods of stray light control

In general, all methods to control stray light in any optical system can be summarized as “Move it” or “Block it” or “Paint/coat it” or “Clean it” [7]. “Move it” refers to moving the object so it is no longer illuminated by the light. “Block it” refers to inserting a baffle so that the object is not illuminated. “Paint/coat it” refers to changing the optical properties of surfaces to change the reflectance or scattered light from a surface and “Clean it” refers to reducing particulate contamination on a surface to reduce its scatter. (In our case, the optics are indeed cleaned to reduce particulate contamination on the surfaces, but the goal here is not necessarily to reduce scattered light elsewhere, but to lower its likelihood of damage from incoming high fluence light.)

3.3.3 Protecting how? (ARC stray light mitigation)

At this point, we are not designing the system from scratch (and as a result do not have a blank slate to work with in terms of redesigning the angles seen by the main beam line). We need to work with the as-designed optical system to mitigate any remaining threats as best as possible, as where the elements go (both optics and hardware) and their physical properties are essentially fixed. Thus, “move it” and “paint/coat it” are no longer feasible solutions. Additionally, all beamline optics and hardware already will be cleaned, so the boundary of the system described in this report includes and is limited by the “Block it” method of mitigation.

Thus, our system is the armor glass system that absorbs the unwanted stray light in the ARC beamlines.

Section 4

System Drivers and Constraints

The main system drivers are the characteristics of the counter-propagating light, reviewed in Section 4.1, and the damage thresholds of the materials, reviewed in Section 4.2, that this light may illuminate. Constraints are reviewed in Section 4.3.

4.1 The counter-propagating light threats are a main system driver

The characteristics of the counter-propagating light must be known in order to mitigate. Table 1 describes in more detail the characteristics of the possible counter-propagating light threats shown in the system context diagram (Figure 6). At the most general level, the light counter-propagating light may originate from either an ARC or NIF source in the target chamber and the threat may be to either an ARC or NIF beamline. This results in four categories of threats and the three involving ARC are listed. (The counter-propagating light originating from a NIF source and entering a NIF beamline was mitigated previously and provided the reference architecture described in Section 3.1.)

Table 1. Categories of counter propagating ARC and NIF stray light threats. The counter-propagating threats that enter the ARC beamlines are shown outlined in green.

Category	Source of CP light	Wavelength (nm)	Mitigation
ARC source into NIF beamline	ARC specular reflection	1053	Managed by backlighter and laser geometry
NIF source into ARC beamline	NIF specular reflection	1053, 527, 351	Managed by target and laser geometry
	NIF SRS	450-700	ARC counter-propagating stray light mitigation system
	NIF SBS	351-361	
ARC source into ARC beamline	ARC SRS	1200	ARC counter-propagating stray light mitigation system
	ARC SBS	1053	

The first row of Table 1 lists ARC counter-propagating light entering the NIF beamlines and since it does not involve the ARC beamlines, it is outside our system boundary described in Section 3.3. The next two categories include CP light that could threaten the ARC beamlines. The threat of NIF specular reflected light directly entering an ARC beamline will be prevented by managing the target and laser geometry inside the target chamber. The last four rows summarize the sources of counter-propagating light in the ARC beamlines for which the ARC stray light system must be designed to mitigate. Included are Stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS) from both the NIF and

ARC beamlines. Each of these occurs over a different wavelength region, which is well-known. The most-challenging threat to mitigate in the ARC beamline is the counter-propagating Stimulated Brillouin Scattering because it is the same wavelength as the forward-propagating laser beam and thus, can easily travel far back up the beamline, as described in Section 3.2.

4.1.1 ARC CP Source characteristics

The source characteristics for the counter-propagating light entering the ARC beamlines (one of the active stakeholders) are given by the ARC Backscatter working group. The wavelength of the NIF and ARC SBS and SRS light is well-known. The cone angle of the counter-propagating light and its peak fluence at the entrance aperture to the ARC beamlines (the Disposable Debris Shield "DDS") also drive the design of the mitigation system; however, the values listed in Table 2 are only estimates. Some system risk (Section 10) is caused by lack of knowledge in this area.

Table 2: Source characteristics

Category	Source	Wavelength (nm)	Peak Fluence at the DDS (J/cm^2)	Cone Angle (degrees)
NIF source into ARC beamline	NIF SBS	351-361	0.38	±4
NIF source into ARC beamline	NIF SRS	450-700	0.38	±4
ARC source into ARC beamline	ARC SRS	1200	0.88	±1in x, ±2 in y
ARC source into ARC beamline	ARC SBS	1053	0.925	±1in x, ±2 in y

Though not listed in Table 2, both the polarization and the pulse length of the counter-propagating light is expected to be the same as the forward-propagating laser light. (The laser has s-polarization in the compressor vessel and the pulse length may range from 1-30 ps.)

The fluence from the counter-propagating sources at the DDS is also not known with certainty, as it will vary will angle and there may be local hotspots due to coherent addition ("speckles"). The amount of light forward-propagating in the laser is a parameter that is well understood and with some assumptions, the peak fluence of the light that returns from the target chamber to counter-propagate down the beamline may be bounded. Calculations in the Appendix show how these peak fluence values are derived from the forward-propagating beam energy for the ARC SBS. The peak fluence values shown in the table are conservative: High estimates were used for the average fluence (an order of magnitude above a more likely estimate) and on top of that and modulation factors to account for speckles were included. (Modulation of 4× was used for ARC SBS and SRS, and 2× for the NIF SBS and SRS.)

For the ARC sources (last two rows of Table 2), the light scattered back into the laser is assumed to originate from a point source centered at the location of where each beamlet was pointed with some cone angle. Each beamlet may be pointed to the same or to different locations (backlighters). The cone angles of the light scattering back into the beamline (SBS and SRS) were assumed to always be twice that of the incoming light. This results in some very important implications (discussed in Section 7). Based on geometry at AM8 (ARC mirror #8), we find that:

The cone of counter-propagating light from one beamlet is wide enough to enter the neighboring beamlet in the same beamline, but not wide enough to enter a neighboring beamline.

This geometry is shown in Figure 12. The cone angle for the counter-propagating ARC light is twice that for the forward-propagating light, which (for ARC) is divided into two beamlets per beam. Thus the cone angles for counter-propagating light listed in Table 2 have directionality.

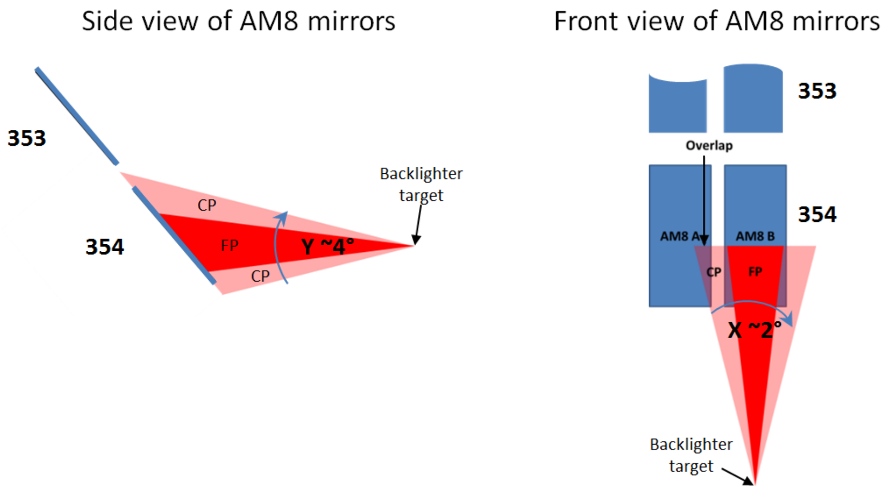

Figure 12: ARC Counter-propagating light cone angles shown for beamlet B354B. Counter-propagating light from this source may enter the B354A aperture, but is not wide enough to enter any of the other beamlines (of which the closest is B353 and is shown).

When light from a backlighter target for one beamlet re-enters the aperture of the beamline for that beamlet, the AM8 mirror used for pointing is directed at the point source of the counter-propagating light. Thus, that mirror keeps the light pointed through the system with the same angles as the forward-propagating light. The AM7 mirror collimates the light and it travels through the system "on-axis." This light goes through the TSF pinhole and is eventually blocked by the PEPC optical switch.

If the two beamlets in one beamline have different backlighter targets, then the light from one backlighter may illuminate the AM8 mirror of the other beamlet. Since that AM8 is pointed to a different location, it will send the light back into the laser at a different field angle. Additionally, the AM7 mirror for focusing may not be set at the correct position to collimate this light. This light is the main threat that can illuminate hardware in the beamline.

4.1.2 ARC CP Source characteristics – point source of origination of ARC CP light

The next system driver, or characteristic of the ARC counter-propagating light is the location from which it originates. As mentioned in the previous section, the counter-propagating light is assumed to originate from a point source that is located at the pointing location of each of the eight ARC beamlets. Each of the eight AM8 mirrors controls the pointing for that beamlet. The "ARC pointing volume" inside the target chamber was defined based on a range of anticipated backlighter positions. The ARC pointing volume is limited by the allowed range of the AM8 motions and is approximately 180mm × 200mm × 88mm and is described in more detail in a configuration-managed NIF document.

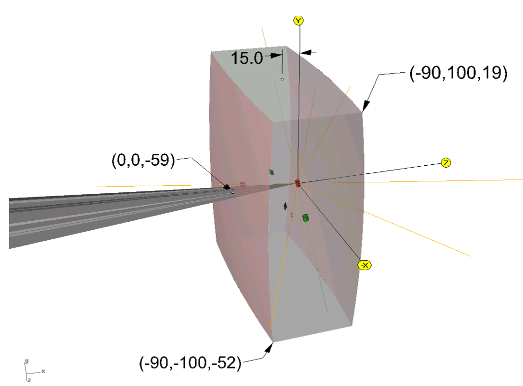

Figure 13: The ARC pointing volume in the center of the target chamber.

4.2 Damage thresholds of materials

Every material has some unique laser damage threshold, where light above some fluence will cause some sort of damage. Optics and coatings usually have very high damage thresholds. The materials of concern here are for the hardware that supports the optics (metals that can ablate) and the absorbing glass that is the main component of the stray light mitigation system. Testing has been done to measure the damage thresholds in these materials; however the results are highly dependent on many factors, including surface finish, angle of incidence, wavelength and polarization of light, pulse length, and environment (air vs. vacuum) to name a few. As an example, Table 3 shows a collection of some measured and unknown laser damage thresholds.

Table 3: Measured laser damage thresholds and armor glass design criteria. Super Grey is the absorbing "armor" glass used for NIF and ARC and "ball mill and etch" is a process that leaves a diffuse surface finish on the glass. NG-1 and NG-4 are other absorbing glass types.

		Laser damage threshold at 1053 nm, J/cm2						Armor glass design criteria	
		ARC					NIF	ARC	NIF
		1.7 ps		10 ps		30 ps	3 ns		
		5 deg	45 deg	5 deg	45 deg			max	max
Super Grey	air	4.4	5.2				53	4	~10
	vacuum							4	
	ball mill & etch						11	???	~4
NG-1	air	4.9	6	11.8	14.5			4	
NG-4	air		5.1					4	
	vacuum		7.7					4	
aluminum	air			0.17				0.08	0.1
	vacuum	0.09 +/- 0.02		0.32		0.09 +/- 0.02		0.08	

s polarization unless otherwise noted

The last two columns of Table 3 are the requirements for peak fluence that will be listed in Section 8 and are included here for comparison to the measured laser damage threshold. The second to last column in Table 3 lists the armor glass design criteria used for ARC during and after compression to short pulse lengths. The final column lists the criteria used for NIF (long pulse lengths) and also for the ARC beamlines when long pulses are expected. (As short pulse light travels backwards from the target chamber through the compressor vessel, the compression process is reversed and it is stretched in time.)

4.3 Important Constraints

4.3.1 No changes to NIF or ARC beamline (path of light through optics)

This system cannot require the laser to be redesigned. For example, we cannot change the positions, angles, or coatings of the optics. It would also be easy to block the aperture of the system to block all counter-propagating light and we'd be done, however that would block the forward-propagating laser.

4.3.2 Space constraints

Space constraints are a related constraint to the first constraint of not modifying the beamline. In order not to block any part of the forward-propagating laser light a stay-out volume was defined. This volume, known as the "Wegner beam," follows the ARC beamline and includes margin for optics installations/misalignment tolerances, etc. Later, a "Rushford beam" was defined as another stay-out zone, defining the path of a separate beam used during the gratings alignment process. In many areas in the compressor and parabola vessels, space is very tight and there is not much room for absorbing glass. Other areas, such as the ABE and NIF beamlines, have more space available, but the beamlines are not very accessible (e.g. confined space permits would be required for installation).

4.3.3 Schedule/Time constraints

The system must be in place in time for commissioning and ARC shots in spring 2015. This required armor glass designs to be completed by summer 2014, ordered, delivered and installed during a planned facility maintenance period in late October/early November 2014.

4.3.4 Budget constraints

The ARC stray light mitigation system, like all systems has an available budget. The budget covers both salaries for employees in the design process and for the hardware that needs to be purchased and installed, though I don't have figures to include here.

The limited budget requires balancing priorities – we can't spend the entire budget doing analysis forever and not buy any hardware. Conversely, it wouldn't make any sense to do no analysis and just line the entire beamlines entirely with armor glass. The amount of glass, mounting hardware and engineering to install it all would be huge. (Probably we would find there are other facility constraints as well from the added weight of the glass somehow distorting the beamlines.)

In the end, budget constraints (or perhaps just fiscal responsibility) caused no armor glass to be installed yet in the argon portion of the beamlines (between the VW1 vacuum window and the TSF pinhole). Armoring the argon beamline to the TSF pinhole area would be a major effort and should only be done if there is a true need. The portions of the beamlines that are filled with argon were not really designed to be vented and refilled frequently. The entire volume of argon currently in the beamlines would be purged (would not be captured) in order to perform the armor glass installation. During that time (e.g. weeks?), the purged beamlines would be unavailable for NIF shots.

Section 5

Operational Scenarios

For the ARC CP stray light mitigation system, there is one input (the counter-propagating light source) and no outputs. There are no subsystems that need power or send and receive data signals to perform any other functions. The complexity in the system arises from the variety of characteristics the input light may have and the variety of possible paths it may take through the beamline. Simple sequence diagrams are shown in Section 5.1. The diagrams showing wavelength scenarios (Section 5.2) and source field angle displacement scenarios (Section 5.3) were very useful gaining concurrence during the system design phase.

5.1 Sequence diagrams for the stray light mitigation system

5.1.1 The simplest use-cases, showing the system capability to absorb light

In the simplest case, counter-propagating light is input into the system and it is absorbed, as shown in Figure 14.

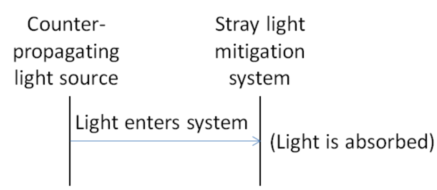

Figure 14: Simplest use case showing system capability.

In a more descriptive use case (Figure 15), the counter-propagating light is shown to propagate through different surfaces in the ARC beamline before eventually being absorbed after AG1. This case shows light following the standard optical path counter-propagating through the system. It is limited because it does not show how the fluence of the beam changes as it propagates through the optical system and there are very many versions that could show light being absorbed after propagating to different locations in the beamline. The diagrams in Section 5.2 show these different scenarios more clearly.

In the ARC stray light mitigation system, timelines are not an important consideration during operation. It is expected that the mitigation system (the armor glass) will be in place after installation and subsequently ready for shots at any time. The armor glass is a passive system and does not do anything other than absorb the light when it arrives (and turn it into heat). There are no moving parts or timeframes for data processing that need consideration. The amount of time that it takes light to counter-propagate through the system can be calculated based on the speed of light and the distances involved, but will not be further discussed here.

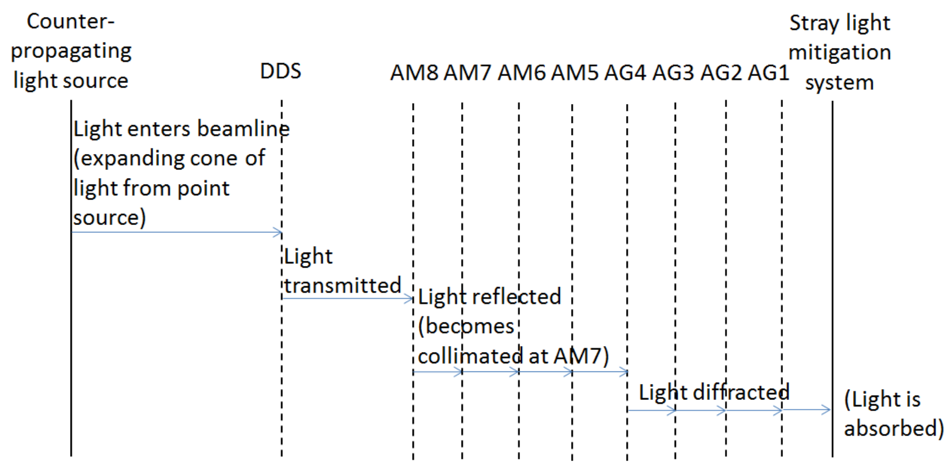

Figure 15: Use case showing light propagating through surfaces in an ARC beamline before being absorbed by the stray light mitigation system after AG1.

5.2 Counterpropagating light scenarios: wavelength dependence

The division of the counter-propagating light fluence at an ARC optic is determined by the properties of the optic coating (reflective or anti-reflective). Each coating is strongly wavelength-dependent. At each surface, light may be either transmitted ("T") or reflected ("R"). Light must be conserved, so T+R=1. Additionally, light transmitted into a material can be absorbed ("A") in the bulk glass substrate.

Simple calculations were presented to the stakeholders to show where the input energy went. These calculations helped verify the both the assumptions about the counter-propagating light source parameters (fluence at each wavelength) and parameters in the detailed optical ray-tracing model and they were used to gain concurrence among stakeholders that the detailed models were working correctly. Since the coatings are strongly wavelength dependent, a separation calculation is done for different wavelength regions of interest. These "first-order" calculations make many assumptions, such as: 1) the fluence is calculated for surfaces normal to the direction of propagation, and 2) the percent reflection and transmission is independent of angle of incidence.

The diagrams in the sections below track the light counter-propagating down the ARC beamline for four different input scenarios: wavelengths of 3w, 450-700nm, 1200nm and 1w, one for each of the different categories of threats in Table 2. In each case, the light is tracked until it is absorbed or the fluence goes well below the maximum allowable fluence determined for metal of 100mJ/cm^2.

5.2.1 3w light

Figure 16 shows the scenario for 3w CP light entering the ARC beamline. The coatings for the final ARC optics in the parabola vessel were designed to be highly reflective for 1w (1053nm) light, the ARC wavelength, but not highly reflective at 3w (R=12%). This decision was made early on to mitigate unwanted 3w (351nm) light counter-propagating back into the ARC beamline. In addition, the bulk glass used for the AM8 mirror is "solarized," meaning that the glass absorbs most of the 3w wavelength through the bulk of the material. Very little light exits to the AM8 backplane. Most of the remaining light reaching AM7 is transmitted through the glass; Very little light is reflected down the beamline any farther and detailed modelling supports this.

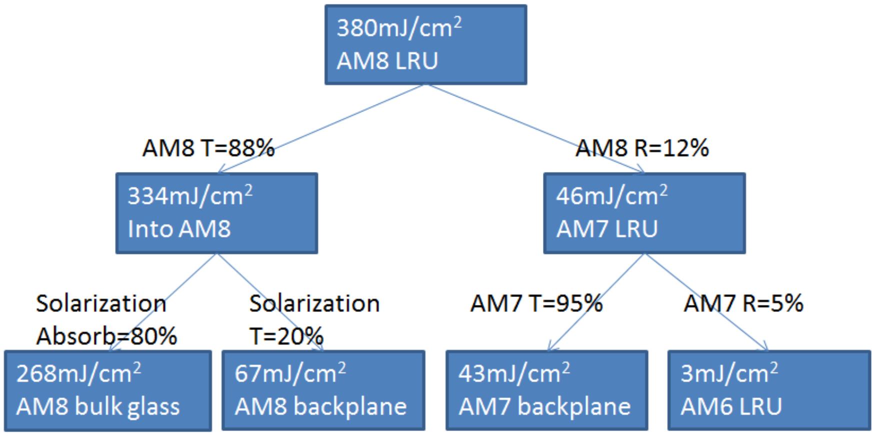

Figure 16: 3w counter-propagating light scenario. (Calculations assume unpolarized light.)

5.2.2 450-700nm light

Figure 17 shows the values in the calculation for the NIF 450-700nm are nearly identical as those found for 3w. Again, most of the light is absorbed by the AM8 substrate and there is negligible light transmitted to the CV, confirmed by the detailed modeling.

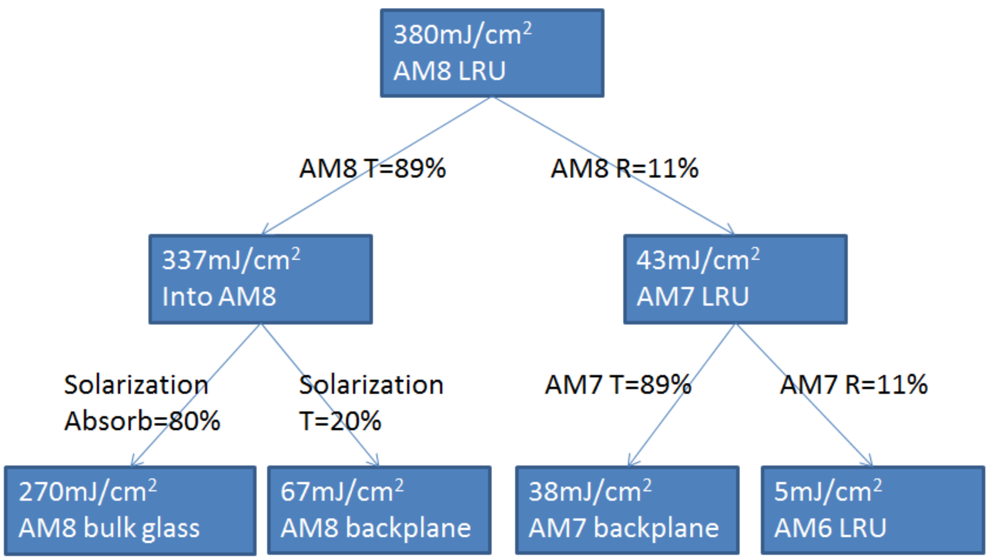

Figure 17: 450-700nm counter-propagating light scenario. (Calculations assume unpolarized light.)

5.2.3 1200nm light

At 1200nm (ARC SRS), the peak fluence of the CP light is more than twice as high as at 351-700nm. Additionally, the coatings are not as effective at blocking transmission of this light down the ARC beamline as for the shorter wavelength threats, so the light travels farther upstream.

As shown Figure 18, there are significant fluence levels of 1200nm light at the backplanes of AM8 (208mJ/cm^2), AM7 (232mJ/cm^2) and AG4 (76mJ/cm^2). AG4 is a grating and at 1200nm, light may only be transmitted or reflected at the surface. There are no solutions to the grating equation for this wavelength, so there are not any diffracted orders possible. (No light can pass through the compressor vessel gratings at the wrong wavelength.) Any light reflected by the grating is directed to armor glass and the simple calculation does not go any farther.

The transmission and reflection values shown in Figure 18 assume unpolarized light; however the coatings for the AM8, AM7 and AM5 mirrors are very polarization dependent. If the ARC SRS is polarized, then the fluence would be divided differently between the AM8, AM7 and AG4 backplanes.

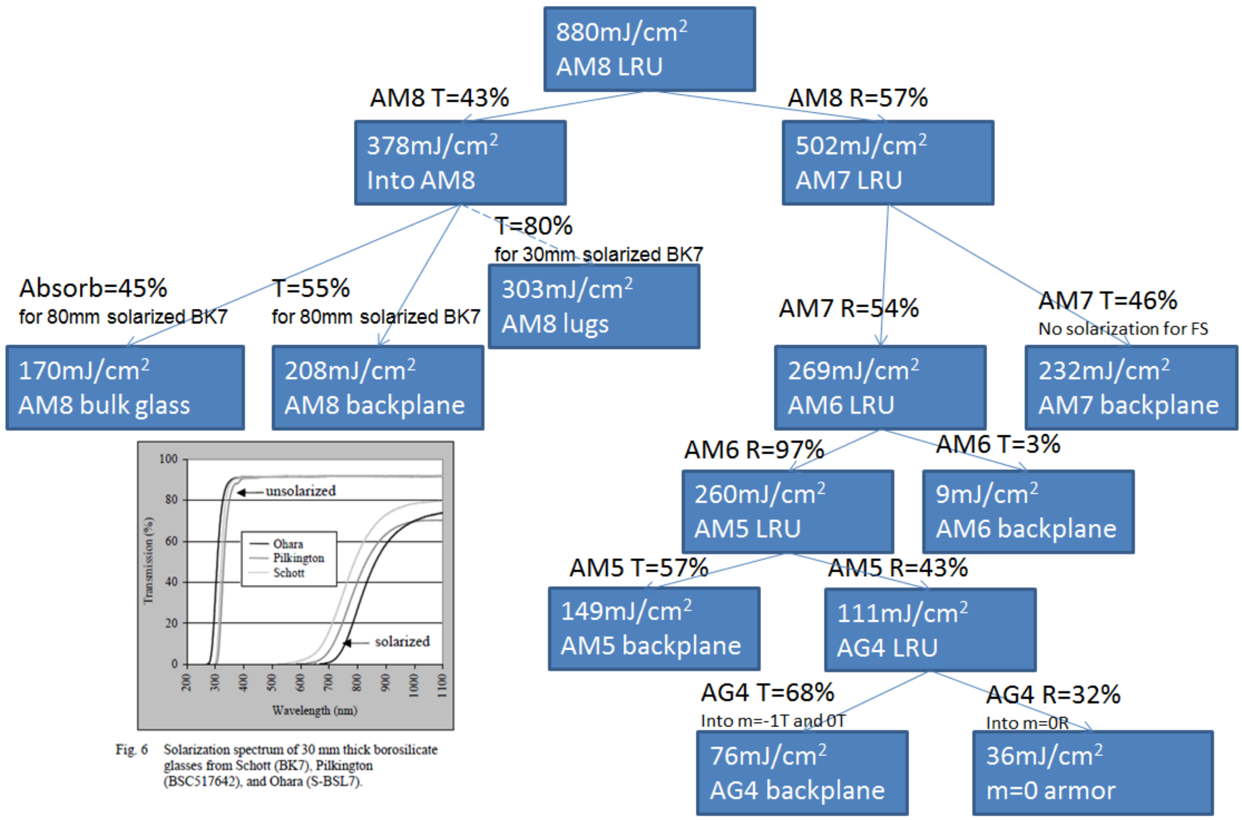

Figure 18: 1200nm counter-propagating light scenario. (Calculation assumes unpolarized light.)

5.2.4 "1w light" includes 1053nm with ~5nm bandwidth

ARC was designed to operate at 1w, so the beamline very efficiently counter-propagates the Stimulated Brillouin Scattering at this wavelength. The following scenario in Figure 19 shows how most of the light in this bandwidth is transmitted through the PV, through the CV and back up the beamline, assuming the light is unpolarized.

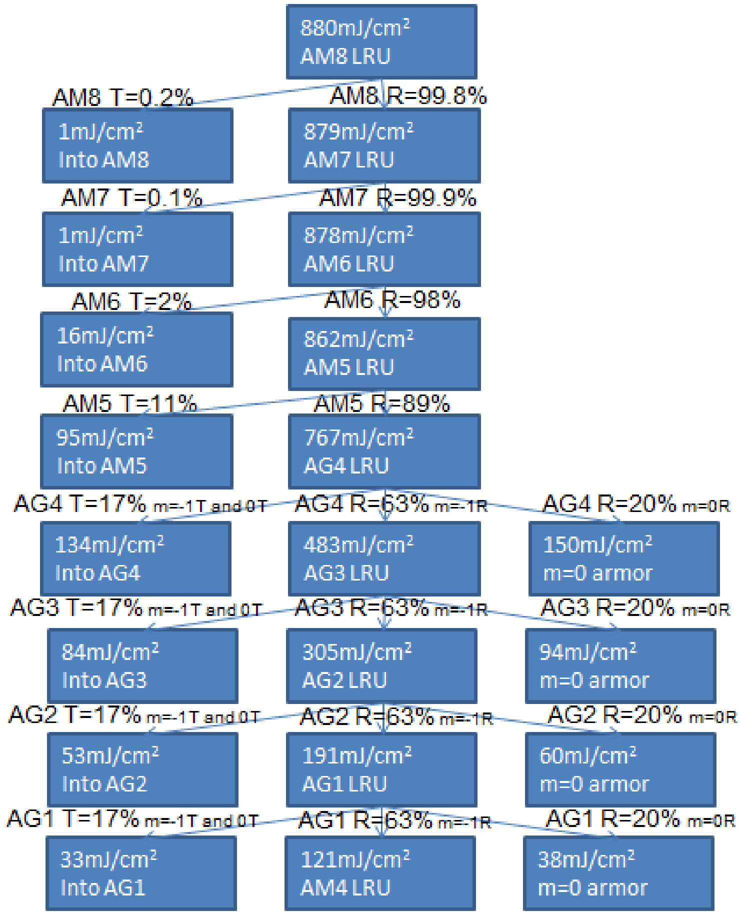

Figure 19: Scenario showing 1w counter-propagating light. This calculation assumes the efficiency at each surface for unpolarized light, though the actual counter-propagating light is expected to be polarized, so it is no longer considered correct. (At the gratings (AG1-AG4), the light is diffracted into different orders (m=-1 and m=0) which may be either transmitted (T) into the substrate or reflected (R). The m=-1 reflected diffracted order is the one that propagates the light through the compressor, while the m=0 reflected diffracted order, corresponding to specular reflection, goes to the absorbing armor glass.)

The scenario shown in Figure 19 ended up leading to significant discussions about the stakeholders about the polarization properties of the counter-propagating 1w SBS light. The light that passes through the CV (e.g. 121mJ/cm2 at AM4 LRU above) was smaller than expected from one stakeholder, which led the team to understanding that the 1w SBS light was expected to be vertically polarized at the target (i.e. s-polarized in the compressor vessel). With this assumption for the polarization, the grating efficiencies increase the light propagated through the CV to nearly 500mJ/cm^2. Additionally, this figure is outdated because the light entering the system (880mJ/cm^2 at AM8) is incorrect; the latest agreed-upon value is 925mJ/cm^2 at the DDS (as shown in Table 2).

Though this model for the grating efficiencies leads to more light "bouncing around" the compressor vessel to the armor glass than expected, it was reasonable to use during the CV armor design phase because it may only over-estimate the fluence on hardware in the CV. Thus, the armor glass design will be sufficient to protect metal in the CV, even in the case of a damaged grating (100% reflective into m=0 reflected order) or unpolarized counter-propagating light. There is no risk for the design being insufficient if the actual polarization is not as expected.

When considering 1w SBS light counter-propagating through the compressor vessel and farther up the beamlines, the assumption that the counter-propagating light is polarized the same as the forward-propagating light it is more conservative. That ~500mJ/cm^2 1w light is transmitted upstream into the Ambient Beam Enclosure (ABE) was found to be a significant threat and much of the further detailed (ray-tracing) simulations were done for this bandwidth.

5.3 Counter-propagating light scenarios: source angle dependence

Another graphical method was useful for convergence between stakeholders and the understanding of the systems engineers about the importance of the source position of the light and where the light exits the aperture of the optics.

One way to view an optical system is to "unfold" it, as shown in Figure 20. Mirrors that just repoint the light can be ignored and mirrors that focus or collimate light can be shown as thin lenses.

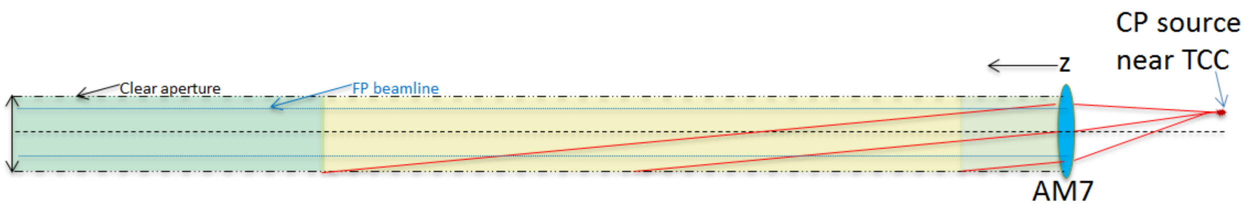

Figure 20: Unfolded ARC beamline. The red lines show the counter-propagating light emanating from a point near TCC. How far off-axis the CP light is for the beamline determines how far away from AM7 (z) it will exit the clear aperture of the optics and become a threat to hardware.

Using an assumption that every optic has the same clear aperture gives a rough look at where sources emanating from different positions may threaten hardware in the system. This was a helpful tool for discussions and increasing understanding of the problem in the team, though not incredibly accurate. (Not only do different optics each have different clear apertures in the x and y directions, beams diffracting off gratings experience magnification changes.) The ABE and beyond (AM3 and below in the figure) will be threatened by light with some range of source displacement (e.g. 10-70mm for AM5).

Different regimes were identified. Small source displacement (light green in Figure 20 and Figure 21) is not a threat because all the counter-propagating light is within the beamline clear apertures (and will go through the TSF pinhole if the displacement is small enough). If the light is exiting the aperture (indicated by yellow), then hardware may be illuminated by the high fluence beam and armor may be required in this area. Finally when the source displacement is large enough (dark green), all of the light has already exited the clear aperture and is no longer a threat.

These conclusions helped guide the decision to allow different operating regimes for the source positions, based how much of the beamline had armor installed. This impact is discussed in Section 7 and Section 9.

		source displacement (mrads) w.r.t. AM8 pointing												
		16.799	14.559	12.319	10.080	7.840	5.600	4.480	3.360	2.240	1.120	0.560	0.336	0.056
		source displacement (mm) w.r.t. AM8 pointing												
Optic/ component	Z wrt AM7 (cm)	150	130	110	90	70	50	40	30	20	10	5	3	0.5
AM7	0													
AM6	115.00684													
AM5	316.59651													
AG4	975.05383													
AG3	1377.9824													
AG2	1680.5744													
AG1	2200.1028													
AM4	2570.833													
AW1	2835.833													
AM3	3007.833													
AM2	3204.268													
AM1	3393.874													
RP18	3695.57													
LM5	4886.094													
LM4	5734.5574													
DBS	5754.2448													
SF4	8055.2498													
TSF	11070.25													
CP Focus distance from TSF Pinhole (mm)									101.299	67.5328	33.7664	16.8832	10.13	1.68832

LEGEND
CP in beamline
CP illuminating edges
CP already scraped off

Figure 21: First order look at the effect on source position and where hardware in the beamline may be threatened. Yellow boxes indicate threatened area.

Section 6

Implementation Concepts Selected and Rationale

The implementation concept selected for the ARC stray light mitigation system was a collection of absorbing armor glass panels, installed throughout the beamline. The armor glass locations and dimensions are chosen in order to ensure the peak expected fluence, determined by the detailed optical ray trace model, does not exceed the maximum allowed fluence on any surface. Section 6.1 summarizes the analysis process and Section 6.2 summarizes the armor glass installation in the parabola and compressor vessels.

It is a passive system that absorbs the unwanted light near the physical location where hardware is threatened. Actively blocking the light at the entrance aperture to the beamline is not possible given the sacred expectation of not impeding the operation of the forward-propagating laser beam. There is not a shutter that can operate fast enough, given the short time frame allowed after the forward-propagating pulse and before the counter-propagating pulse.

6.1 Expected peak fluence calculated through modeling

The optical model includes detailed parameters for the counter-propagating sources and all of the optical elements to model the actual light propagation. In the optical model, light can be reflected, refracted, transmitted, absorbed, or scattered at every surface. The entire optical system was modeled using a non-sequential optical ray-tracing program. As each ray propagates in a non-sequential model, the software checks all surfaces to see which one the ray will intercept next (as opposed to a sequential optical model, which just traces a ray through lens 1, lens 2, lens 3, etc. in the order as defined by the designer). The energy of each ray is tracked as it is propagated through the system (and splits at multiple interfaces).

First the model is built (Section 6.1.1), and then the ray-tracing runs are done (Section 6.1.2).

6.1.1 Building the model

Building the model is the process of inserting all components (both optical and hardware) and assigning optical properties. The optical coatings are modeled so that the correct percentage of light is propagated in every allowed direction at each interface (i.e. percentage reflection depends on wavelength, angle of incidence, polarization etc.).

It is necessary to insert all hardware into the optical model in order to see which hardware may be illuminated by counter-propagating light. IGES files for all the hardware (components that are not an optic) from the mechanical designers were transferred to the optical engineers to be imported into the optical model. These IGES files would make the optical model “too heavy” if every last screw was included, so the surfaces in the mechanical models were often simplified to keep the model manageable. If an area is found to have light incident on it, more detail was added as needed. Surfaces closer to the optics usually had more detail (e.g. keep a washer used for armor glass mounting but ignore entire frames that are behind the optics). The mechanical engineering team reviewed the optical models to ensure nothing is missing. In general at non-optical surfaces, light can be scattered over wide angles. However, for the counter-propagating light levels here, wide-angle light scattered in all directions will have negligible fluence at the next surface intercepted. For the sake keeping ray-tracing run times reasonable, all wide-angle surface scattering is ignored and metal hardware was set to absorb ("halt all rays").

As armor glass locations and dimensions are identified, the armor and its mounting hardware was also imported into the optical model to verify the high fluence light previously hitting metal was indeed mitigated. Armor glass originally was set to "halt all rays" but was later refined to allow specular reflections, which can be efficient for near-glazing incidence light.

6.1.2 Ray-tracing runs

Once the optical model is built, rays can be traced through the ARC beamlines. The variables for each run were the pointing of the AM8 mirrors and the location of the point sources from which the counter-propagating rays originate from within the ARC pointing volume. A 5x5 matrix of AM8 pointing and source locations was used to identify surfaces that were threatened by high fluence in the parabola vessel and compressor vessel. Absorbing glass was then proposed by optical engineering to mechanical engineering to protect the area. Mechanical engineering would then add armor glass and the necessary mounting hardware to their model, sometimes modifying the size or position as needed to fit in the area. The new armor glass and mounting hardware would then be transferred as IGES back to the optical model to ensure that the previously threatened hardware was now protected and to identify any new threats. Some of the new threats identified were to the mounting hardware for the armor and to other areas in the vessels due to specular reflections from the armor glass at grazing incidence. When the armor glass mounting hardware was threatened, the hardware location was redesigned to a safer location. When specular reflections from the armor glass were identified to threaten other areas, the armor was chosen to have a diffuse surface finish.

6.2 Armor glass installed

Design and installation for the armor glass inside the parabola vessel (PV) and first compressor vessel (CV2) was possible because these vessels were currently being commissioned. The scheduling and funding constraints has not yet allowed ABE to the TSF pinhole to be armored. This impact will be discussed in Section 7.

6.2.1 Parabola Vessel (PV)

125 pieces of armor glass were installed in the parabola vessel. These are listed in Table 4 and shown in Figure 22.

Table 4. Armor installed in Parabola Vessel

Area	# pieces
Near AM6	7
AM7 frame	15
AM7 trimmed	1
AM7 CAPS upgrades	8
AM8 frame	6
AM8 LRU	52
PV exit	4
AM7 clips	16
AM6 clips	16
Total	125

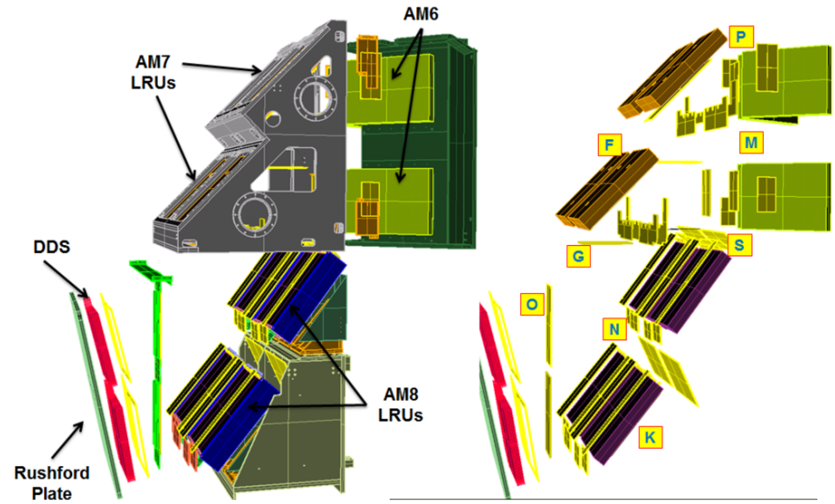

Figure 22: Armor glass (shown in yellow) in the parabola vessel.

6.2.2 Compressor Vessel (CV2)

109 pieces of armor glass were installed in the compressor vessel 2. These are listed in Table 5 and shown in Figure 23. Figure 24 shows a photograph of the armor installed around the gratings AG2 and AG4.

Table 5: Armor installed in Compressor Vessel 2

Armor location	# pieces	Size (mm)	Chosen Finish
Back wall panels	3	650x650	Diffuse
AM5 leak	2	620x660	Diffuse
AM5 leak center patch	1	630x225	Diffuse
AG2/4 panels	4	620x660	Diffuse
AG2/4 end pieces	2	60x646	Diffuse
AG2/4 center patches	2	630x225	Diffuse
AG2/4 end center patch	1	83x225	Diffuse
AG1 front panels	4	235x745	Standard
AG1 back panels	4	240x480	Standard
AG3 panels	2	615x745	Standard
Grating LRU	40	various	Standard

Armor location	# pieces	Size (mm)	Chosen Finish
AM4	3	various	Standard
AM5	16	various	Standard
CAT	23	various	Standard
Vacuum window	2	various	Standard
Total	109		

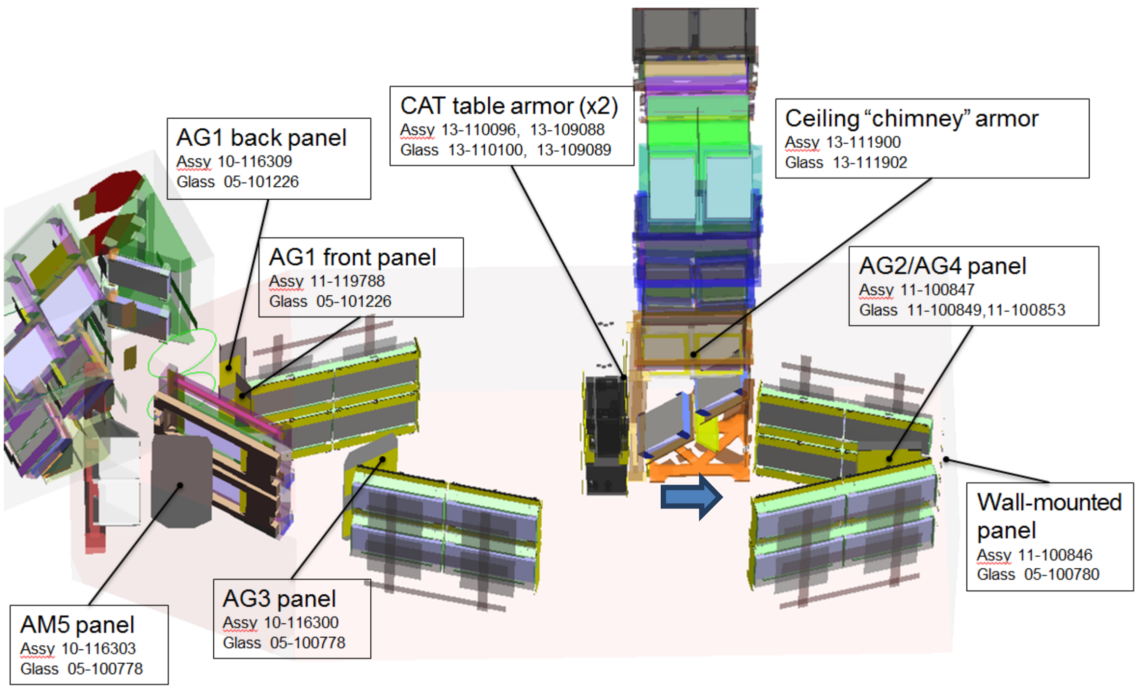

Figure 23: Armor glass (shown in yellow) in the compressor vessel. The blue arrow shows the direction of view for the photo in the next figure. (Drawing numbers are shown for a selection of armor glass panels.)

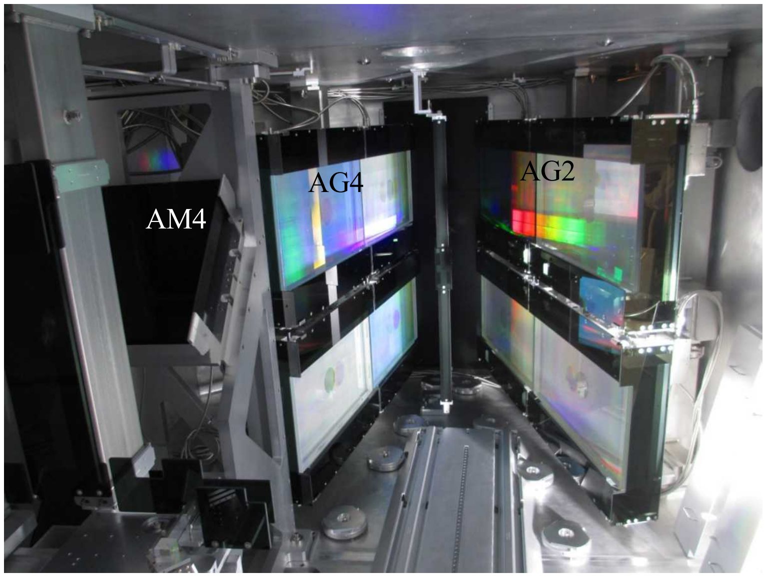

Figure 24: A photo of the compressor vessel with armor glass installation complete. The armor glass surrounds the gratings (seen with rainbow reflections). The armor appears black because light does not transmit through the material.

Section 7

Proposed System Operational Architecture

The operational architecture for the armor glass stray light mitigation system as defined in Section 2 and 3 is quite straightforward. If stray light enters the beamline, then the absorbing glass mitigates it near the physical location where it would become a threat to hardware. However, it is really impossible to separate the laser system from the stray light mitigation system. Once light enters the beamline, the optics transport through the system. The optics are not merely an active stakeholder, but are deeply intertwined as part of the system. The ARC stray light mitigation system is a small subsystem in a very complex laser. I did not include the laser itself within the system boundaries defined earlier because that would cause too much complexity for a class project (so many more stakeholders, operational scenarios, requirements, and risks to describe).

I will use this section to show the operational architecture at a different level to show how our armor glass subsystem fits with in with the overall laser on a larger scale.

7.1 Proposed system operational architecture

There are different methods for controlling unwanted light throughout the ARC beamlines and are summarized in the proposed system operational architecture diagram in Figure 25.

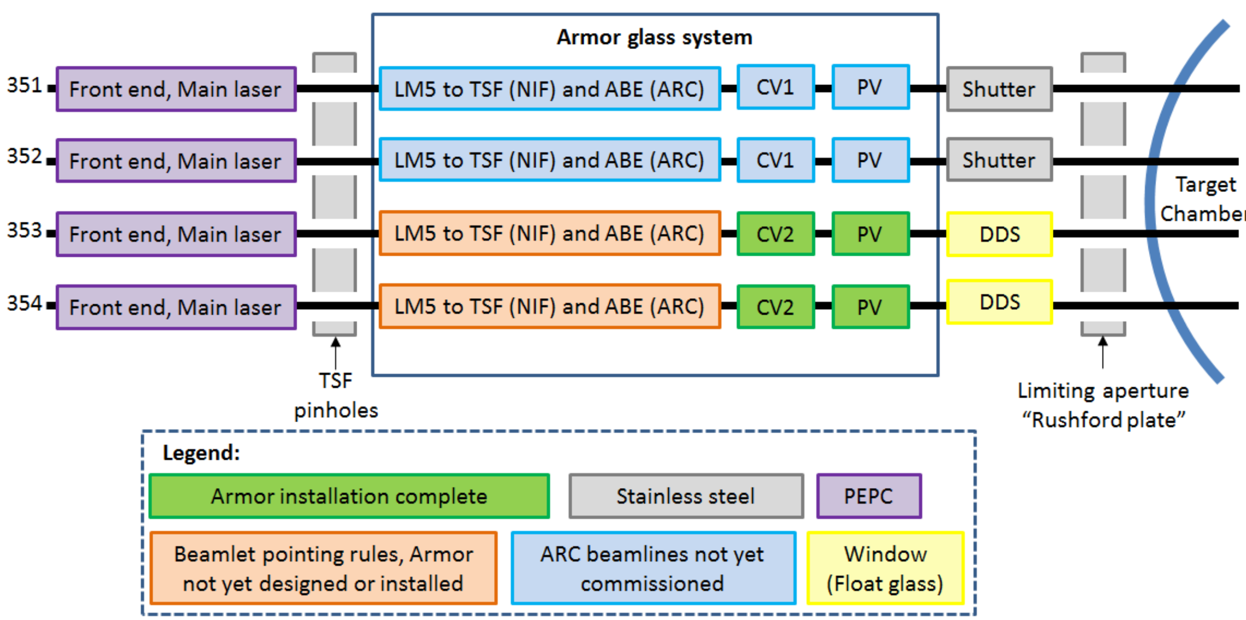

Figure 25: Operational architecture for entire ARC stray light mitigation system. The blue box outlining the armor glass system shows the system boundary identified earlier.

Figure 25 includes legacy architecture for the areas of the beamline that are not changed from ARC and the new elements that are described by the armor glass system of this project. The important elements will be described in the direction followed by the counter-propagating light from the target chamber to the front end of the laser (right to left in Figure 25).

7.1.1 The limiting aperture and debris shields

The limiting aperture for the ARC beamlines is a stainless steel plate, referred to as the "Rushford plate." It is a stainless steel plate outside of the target chamber the limits the extent of the light that enters the ARC beamlines. Material that may ablate off this plate or any other debris existing in the target chamber is prevented from entering the beamline by the DDS, the disposable debris shield. The disposable debris shield is a sacrificial glass window made out of float glass that may be frequently replaced. It is still a high quality optic, but it protects the more expensive optics upstream.

NIF used the same method of having a stainless steel plate (the "Siegel plate") as a limiting aperture for counter-propagating light and a debris shield window, so the reference architecture for this area is unchanged.

For the two beamlines not yet commissioned (351 and 352), a stainless steel plate currently shutters off the beamlines at the DDS location.

7.1.2 Armor glass system in the ARC compressor vessel and parabola vessel

The armor glass system for the compressor vessel and parabola vessel is the next step of stray light protection in the ARC beamline. Absorbing glass is placed in everywhere within those vacuum chambers to prevent high fluence light from illuminating anything other than the beamline optics. The technique is the same as the NIF reference architecture used in the NIF final optics (absorbing glass protecting metal), but the locations of the glass positions is completely new due to the different layout of the beamline itself.

The design and installation for armor for the first two beamlines (353 and 354) is complete. We anticipate copying the design (similar relative armor positions dimensions) for the next two beamlines (351 and 352). Analysis will confirm threats are also mitigated before the final design, procurement and installation.

7.1.3 Armor glass system in the ARC Ambient Beam Enclosure all the way to the NIF TSF pinhole

No additional armor glass has been installed in the ARC ambient beam enclosure (ABE) path for counter-propagating light. There is some armor already installed in places following some best practices (e.g. small armor glass covers on the earthquake retention clips that hold the fold mirrors in place and a few pieces near AM1). Locations where armor is needed for ARC counter-propagating light have been proposed, but there has been no design effort thus far. Had the analysis for counter-propagating light been done earlier in the design phase, the armor could have been installed the same time as the optics. Now the effort to vent this portion of the beamline (now filled with argon) and install armor is more significant.

There is some armor in the portion of the beamlines shared with the NIF optics (Laser mirror 5 (LM5) to the Transport Spatial Filter (TSF) pinholes), but the extent is insufficient for the angles and fluence of the ARC counter-propagating light. In this area, the legacy architecture was designed for NIF threats and is insufficient for the new ARC threats. (The armor from the TSF to LM4 is needed to mitigate reflections of the forward-propagating beam while the armor near LM5 through the NIF final optics is needed to mitigate the counter-propagating light.)

The locations where metal hardware is threatened in both of these areas (the ARC ABE and NIF LM5 to TSF) depend on the input angles of the counter-propagating light. There are some backlighter pointing scenarios where light does not enter in to the system at a threatening angle. If we want to allow any ARC beamlet to point anywhere allowed by the ARC pointing volume, then additional armor is required for full mitigation. Rules have been proposed for operation (Section 7.2) to limit the backlighter scenarios that are acceptable for the current armor glass situation. The rules basically only allow scenarios where the stray light that enter the beamline to be either mitigated by the armor in the CV and PV or to pass entirely through the TSF pinhole and be mitigated by the PEPC.

7.1.4 The Transport Spatial Filter (TSF) pinholes

The Transport Spatial Filter pinholes are stainless steel apertures located at the focus of two lenses that limit angular extent of the light propagating through the main laser, both in the forward and counter propagating directions. Any counter-propagating light that passes through the pinhole will stay in the apertures on the optics and will not further threaten metal hardware in the beamlines. As these pinholes are metal, they themselves can be threatened by the angular extent of the ARC counter-propagating light. Armor glass may need to be installed around the pinholes as well for full mitigation of ARC counter-propagating light.

7.1.5 The PEPC optical switch

An optical switch (the plasma electrode Pockels cell, or PEPC) is timed to only allow the forward propagating beam to pass. It prevents any counter-propagating light, now all "on-axis" from the pinhole from reaching the NIF main amplifiers and traveling amplified all the way back to the delicate fiber optic components in the front end of the laser. The PEPC operation will be slightly changed for ARC, compared to regular NIF operation, to provide additional isolation for the additional 1w counter-propagating light.

7.2 Proposed rules for operation (describing current allowed backlighter locations)

Rules have been proposed (and recently accepted by the stakeholders) to permit only an accepted set of backlighter scenarios. (A backlighter scenario is described by the location of the backlighter targets in the ARC pointing volume for each of the beamlets. For example, one scenario might have all of the beamlets in all of the beamlines co-pointed to the same backlighter target. Another scenario could have each of the eight beamlets pointed to different backlighter targets located throughout the ARC pointing volume.)

These rules are necessary because there is not sufficient armor glass in the beamlines to fully mitigate any possible counter-propagating light. The rules are defined to limit all counter-propagating light to either pass through the TSF pinhole or to exit the beamline in the CV and PV.

The geometry in Figure 12 shows that counter-propagating light from a backlighter in one beamline does not enter the aperture of a neighboring beamline. Thus, there are no limitations on beamlines relative to other beamlines. However, counter-propagating light from on beamlet may enter the aperture of the other beamlet in the same beamline. This is the main counter-propagating light threat in the system and is the reason for the rules regarding the relative beamlet pointing within a beamline.

7.2.1 The operational regimes

The counter-propagating light threat is rectangular, thus the beamlet limitation has directionality.

Two regimes are allowed:

1. Overlapping beamlets or very small beamlet separations – no threat (all stray light goes through TSF pinhole) (no dependent on the size of the overlapping sliver).
2. Larger separations (all light exits in the CV and PV). This is sliver dependent on one axis and focus dependent (more analysis needed).

The slide presented to the ARC stakeholders is shown in Figure 26.

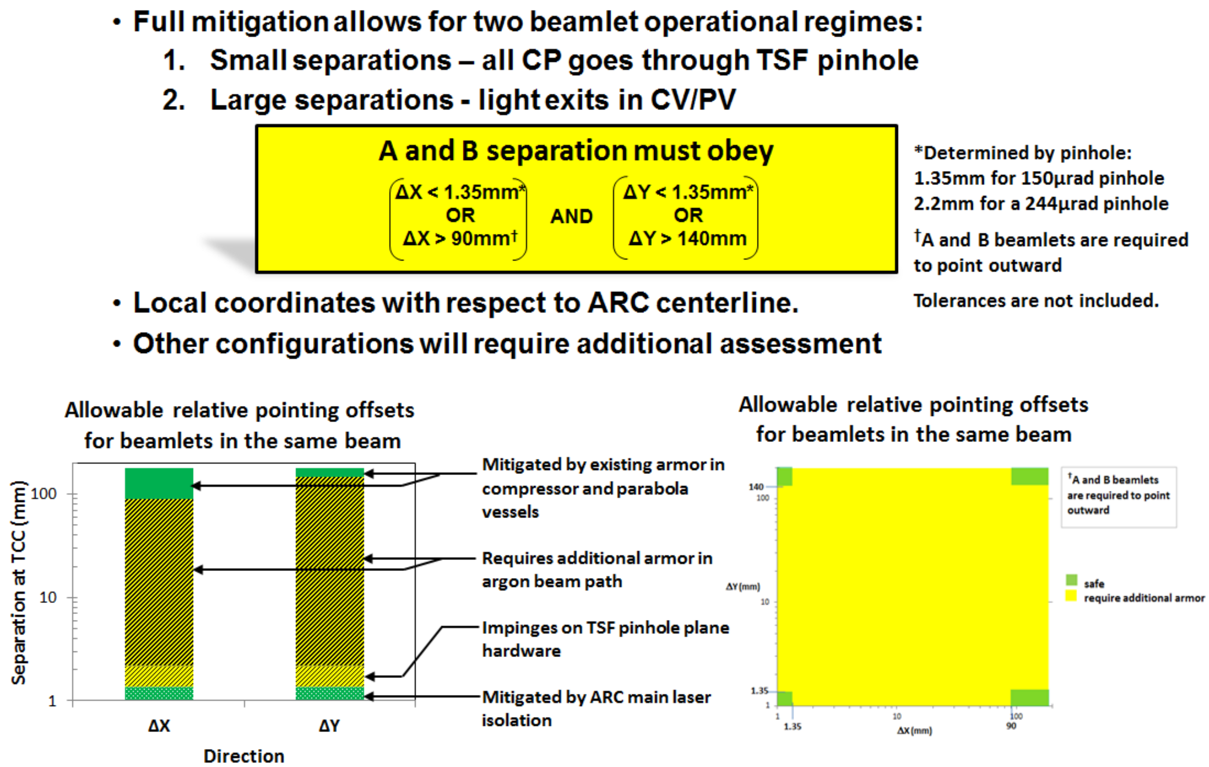

Figure 26: Beamlet pointing rules for operation (slide presented to stakeholders).

The remaining action is the implementation of the rule set in the checklists and software. (There is legacy architecture for managing such rules in software and checklists. We just need the rules themselves to be refined in those places.)

Section 8

System Requirements

8.1 Functional Requirement

The overall ARC cleanliness system (for one level higher than our subsystem, refer to Figure 5) probably has requirements such as1) Particulates < Class A, 2) H_2O < X PPM and 3) Oil < Y PPM.

Our ARC stray light mitigation system requirements are based on minimizing the particulates caused by ablation. The requirement to keep the fluence on each surface below its damage threshold means that ideally no particles are generated from ablation. (The damage thresholds for the materials used in the ARC beamlines are important system drivers and were listed in Section 4.2.) Though it may seem risky that the main requirement (Table 6) is verified only by simulation and modeling, the peak fluence allowed for each material (Table 7) is based on extensive laser damage testing measurements.

Table 6: The main functional requirement for the ARC stray light mitigation system design.

Requirement	Rationale	Verification
The peak fluence expected for every surface illuminated in the beamline must be below the allowed threshold for that material	Desire to minimize ablated particles	Simulation and modeling

Table 7: Peak fluence allowed for materials in ARC.

Material	Peak Fluence Allowed (J/cm^2)
Super Grey (regular finish)	4
Super Grey (diffuse finish)	4
Metal (short pulse: ARC CP light before and in the compressor vessel)	0.08
Metal (long pulse: ARC CP light after stretching in the compressor vessel)	0.1
Polymers (adhesives, PEEK, LPU, black viton, white viton etc.)	0.02

8.1.1 Discussion of metal requirements

The damage threshold for materials depends on the pulse length of the illumination: For a given pulse energy, shorter pulses have higher peak fluence and thus may more easily cause damage. When the laser pulse is traveling down the main NIF beamline toward the target chamber, the pulse length is long (e.g. 20ns) and after compression by the gratings the pulse length is shortened (e.g. 3ps). When the ARC scattered light is counter-propagating, it will originate from the target chamber with the same short pulse length. As this light passes backwards through the compressor vessel, it will lengthen in time. The peak fluence on metal was chosen to be $100mJ/cm^2$ for long pulse light and $80mJ/cm^2$ for short pulse light.

8.1.2 Armor glass requirements

The chosen peak fluence requirement for Super Grey in ARC of $4J/cm^2$ is slightly below the measured damage threshold of $4.4J/cm^2$. The original requirement for peak fluence on armor glass for the NIF final optics was $<2J/cm^2$, however modeling showed a peak fluence of $3.8J/cm^2$ on the armor for ARC. The requirement was increased with the justification that the energetics criteria used to define the threats on the ARC system already includes a conservative margin (2-4x), unlike the counter-propagating light levels used for NIF. The CP light expected to enter the NIF final optics was known with more certainty during the design phase and the margin for that system design was placed instead in the armor glass design criteria instead of the fluence requirement.

Diffuse finish armor glass (from the "ball, mill and etch" process) would be expected to have a lower damage threshold than the standard finish glass. As shown in Table 3, we didn't have measurement results for this material for short pulse length light and the same peak allowed fluence was chosen as the regular finish glass. Although more easily damaged, the diffuse glass is valuable because it can eliminate specular reflections and was deemed to be worth the increased risk.

8.2 Non-Functional Requirements

The non-functional requirements for a system are those that may include transportation, facilities, training and personnel, maintenance, environment, reliability, maintainability, operability, availability, supportability, manufacturability, security and safety, interoperability, or inputs and outputs. A selection of these requirements for those characteristics is shown in Table 8.

The most significant non-functional requirement is that the armor glass installed does not block the forward-propagating laser beam. (This ensures functionality of the ARC laser system itself.) In particular, a 3-D volume was defined as a stay-out zone for armor glass. This volume, known as the "Wegner beam," follows the ARC beamline and includes margin for optics installations and beam misalignment tolerances. Later, a "Rushford beam" was defined as another stay-out zone, defining the path of a separate beam used during the grating alignment process.

Table 8: Some non-functional requirements for the ARC stray light mitigation system.

Requirement	Rationale	Verification
Armor glass must be located outside the beam stay-out volumes, minus armor installation tolerances	No armor will block the forward-propagating laser beam	Analysis
All armor glass mounting hardware shall be >6mm away from high fluence light	Do not want to have the solution be part of the problem	Simulation and modeling
All armor glass mounting hardware uses stainless steel	Higher damage threshold than aluminum	Inspection
Armor glass sizes shall be <x lbs or dimensions	The armor needs to be able to be handled by the installation and maintenance crews	Inspection
Large pieces of armor (>x lbs) shall have handles for ease of handling	Do not want personal or equipment damage	Inspection

Requirement	Rationale	Verification
Armor glass that may need to be removed to remove/install other optics needs to have storage facilities identified	Do not want personal or equipment damage	Inspection
Polymers are buried behind shields (with aspect ratio of greater than 3:1) or are in conduits	Desire to prevent material damage and minimize particulates	Analysis

Section 9

Organizational and Business Impact

9.1 Organizational and Business Impact

The organization has already installed the armor glass system in the ARC compressor vessel and parabola vessel. There has not been much maintenance required for the (legacy) armor glass panels currently installed for on NIF. The organization is used to intermittently examining the panels and beamlines for signs of damage. It will not be a major impact to add another area needing these infrequent levels of required inspection and maintenance.

The largest impact to the organization is that the counter-propagating stray light system does not mitigate every possible counter-propagating threat with armor glass. While the parabola vessel and compressor vessels had extensive armor glass installed for any of the expected stray light scenarios (counter-propagating source may emanate from anywhere within the ARC pointing volume), the Ambient Beam Enclosure back to the Transport Spatial Pinhole (TSF) is not armored. Additional armor would be required in Ambient Beam Enclosure and NIF beamlines to allow for any possible counter-propagating source scenario. The effort (schedule/budget) to armor this area would be extensive.

Rules (new operational architecture shown in Section 7) have been established to describe operating scenarios that are currently allowed. The NIF beamlines also have rules for allowing pointing and it should be possible to implement rules for the allowable ARC pointing in the same manner. (Note this is where the final stakeholder the TALIS group (target and laser interaction) fits in. The TALIS team implements the control of currently allowed pointing.

When an ARC user desires a configuration of backlighter targets and beamlet pointing that is not currently an approved operating scenario, the optical engineering team will need to simulate that counter-propagating light scenario. If no threatened surfaces are found, then the pointing rules will be modified. If threatened surfaces are found for a specific beamlet pointing scenario (and there is not an alternate configuration of backlighters/beamlet pointing that satisfies their experiment) and the experiment is important enough, then the business need will be shown that the expenses are justified for adding more armor. This process of ARC users proposing new missions to optical engineering, doing analysis and modifying the beamlet pointing rules will be new for the organization. While the process will be new, the skill/competencies required for the analysis will not be new. The organization will need to ensure that the optical engineering team will be able to handle this new, ongoing workload and that the ARC users need to realize new missions may need analysis before new configurations are approved. For the near future, all initial ARC missions plan to use overlapping beamlet pointing scenarios, so this is not yet a concern.

Section 10

Risks and Technology Readiness Assessment

10.1 Risk Assessment

The technology needed to manufacture armor glass is proven. The glass is just architectural glass, used widely in building throughout the world and it is not a specialized piece of equipment or a process used in very few laboratories for example. NIF has been implementing armor glass to absorb stray light successfully for many years and there is no question that the technique works.

The risks in this system are primarily due to (Risk #1) the fact that the accurate properties of counter-propagating light in the ARC beamline are unknown and (Risk #2) that the laser damage testing of all the materials has not be performed with the exact same operating conditions (pulse length, wavelength, angle of incidence, surface finish) in every case.

10.1.1 Risk 1 & 2: CP light is higher than expected or angle is wider than expected (paths not identified)

The physics that occur in the plasma in the target chamber from the new ultra-short pulse petawatt laser make it hard to estimate the properties of the scattered light (fluence estimates over orders of magnitude). Also the assumptions about the angles of the counter-propagating light have a big effect on the analysis. We assumed that cross-talk can occur across beamlets, but not beamlines. If the angles of the counter-propagating light are wide enough such that beamline crosstalk occurs, but not so wide that the fluence is greatly reduced, then there may be additional threats to the ABE. We may find that the operational rules defined in Section 7.2 need to be refined. The idea of a back-scatter diagnostic that would help diagnose the counter-propagating threats has been proposed and would help reduce the uncertainty of the needed mitigation, but is not under development. The CV and PV armor was designed to mitigate CP sources for any beamlet or beamline scenario and armor was designed with generous margins, so the risk is smaller in this area. (This is important because these areas contain the expensive gratings!)

10.1.2 Risk 3: Damage threshold is lower than expected

The next risk is that the damage threshold for materials is lower than expected. Laser damage is not something that automatically occurs exactly when some physical threshold is exceeded. The probability of damage increases as the laser fluence increases, according to some statistical probability distribution function, which may be measured during testing. Although small, the possibility for damage may still exist for lower fluence levels. In addition, test results depend on many variables, including wavelength, pulse length, polarization, test environment (e.g. air vs. vacuum), polarization, laser beam size, and surface finish, which may not exactly match ARC. In particular, it may not be entirely appropriate to scale the damage threshold for different pulse lengths. The uncertainty in damage thresholds is probably no greater than ~10% and there were not any places identified where the peak expected fluence was within 10% of the requirement. Therefore this is probably a small risk. At any rate, if there is ablation, then that just increases the probability of particles landing on optics, which increases the risk of damaged optics.

10.1.3 Risk 4: Model fidelity

The final risk is that real life does not match what was built. Only a simplified mechanical model was imported into the optical model for ray-tracing. There was no Monte Carlo simulation to take into account fabrication or installation tolerances for either the armor glass, the metal supporting hardware or the optics themselves. Additionally, though we tested may source scenarios and used as high ray sampling for the ray traces as computationally possible, given a reasonable amount of time, the sampling was not infinite and something may have been missed. A “caveats list” detailing some of these differences was presented and is included in Appendix C.

10.2 Technology Readiness Assessment

The armor glass system is already installed in the CV and PV for ARC - It is not technically challenging to manufacture or install the glass into the beamlines. Where the system-readiness is lacking is in the extent to which the armor has been implemented, partly due to current funding and schedule constraints. (Engineering personnel have been required to work on higher priority projects for NIF.) How to deal with the limited implementation of armor was described in Section 7 with rules for operation (only certain backlighter scenarios are allowed). The technology (software and checklists) needed to implement the rules is place.

Thus the ARC stray light mitigation system passes the technology readiness assessment.

The purpose of the stray light mitigation system is to reduce the risks from known counter-propagating threat paths ablating metal in the beamline. Though it may not be possible to eliminate every possible high fluence spot of light on every piece of hardware in the beamline, the cleanliness in the beamlines is enhanced and the lifetime of the optics is improved.

Appendix A

Definitions and Acronyms

Term	Definition
1w	1053nm. This is the wavelength of the NIF main laser. The ARC pickoff takes this light, compresses it in time and sends it to a backlighter target to create x-rays.
3w	351nm. This light has been frequency tripled in the NIF final optics and is focused to the NIF targets. Some of this NIF light may enter the ARC beamline as a CP threat.
ABE	Ambient Beam Enclosure
AG1-AG4	The four ARC gratings in each beamline. Each of these gratings has two elements (e.g. AG1A and AG1B) for each beamlet. 4 gratings x 4 beamlines x 2 beamlets = 32 gratings total.
AM1-AM8	ARC mirrors #1 through #8. The first ARC mirror AM1 is the pickoff from the NIF beamline. AM2-AM6 transport the beam through the facility. AM7 is the parabolic mirror that focuses the beams to the target. AM8 is the last mirror, actuated to point each beamlet to different locations in the ARC pointing volume.
ARC	Advanced Radiographic Capability
ARC Pointing Volume	This volume describes the possible locations where the ARC backlighter targets may be placed. It was designed based on proposed missions and subsequently slightly modified based on the allowable motion of the AM8 mirrors. It is slightly pillow-shaped with approximate dimensions of 88x188x200mm and defines the possible origination points of the CP sources in the optical modeling
Armor	Absorbing glass placed in the beamlines to protect hardware from stray light
AW1	ARC window 1: This is where the FP light enters the ARC compressor vessel.
B351-B354	The four beamlines (or “quad”) of ARC.
Backlighter	The ARC beamlets are pointed to backlighter targets. When the high peak power light pulse hits the backlighter, x-rays are produced. These x-rays are used to create radiographs of the imploding core of the NIF target, where the rest of the 188 beams are focused.
Beam	This term may be used in general to describe the laser light, but is usually avoided for ARC because of the ambiguity of whether this term refers to a beamlet or a beamline.
Beamlet	Each ARC beamline is split into A and B beamlets with a small gap between them. Thus, there are 8 separate beamlets for independent pointing and timing.
Beamline	There are 192 NIF beamlines, 4 of which are used for ARC.

Term	Definition
CP light	Counter-propagating light. This light originates from the center of the NIF target chamber and propagates back up the beamlines. It is the “threat” that the ARC stray light mitigation system protects and exists in a variety of wavelength bands.
CV	Compressor Vessel: This is where the pulse compression occurs and includes optics AW1-AM5. There are two compressor vessels: Beamlines B353 and B354 are compressed in CV1 while B351 and B352 are compressed in CV2.
DDS	Disposable debris shield, a sacrificial window protecting the parabola vessel from target chamber contamination. This is the entrance aperture into each ARC beamline. When discussing the fluence entering back down the beamline, it is in this plane, unless otherwise specified.
FOA	Final Optics Assembly. These are the final optics the NIF beamlines pass through before entering the target chamber and is where the light is converted from 1w to 3w. (The ARC beamlines bypass this assembly.)
FP light	Forward-propagating light. This light originates from the front-end of NIF and propagates toward the target chamber. It is centered about 1053nm.
LM1-LM8	Laser Mirrors #1 to #8. These are the mirrors in the NIF main laser. The ARC beamlines are amplified in the NIF main laser and travel to the ARC pickoff mirror, which is after LM5.
NIF	The National Ignition Facility
PEPC	Plasma Electrode Pockels Cell: This is an optical switch in the main beamline that can block the counter-propagating light from propagating to the ARC front-end
PV	Parabola Vessel: This is where the beamlets are pointed and focused onto the backlighter targets and includes optics AM6-AM8.
SBS	Stimulated Brillouin Scattering: This scattering occurs from the target in the same wavelength band as the incident light. Both NIF SBS (351nm) and ARC SBS (1053nm) are sources of counter-propagating light threats in the ARC beamlines.
SRS	Stimulated Raman Scattering: This scattering occurs from the target in a longer wavelength band as the incident light. Both NIF SRS (450-700nm) and ARC SBS (~1200nm) are sources of counter-propagating light threats in the ARC beamlines.
TCC	Target Chamber Center. The NIF and ARC beams are focused to targets in a small pointing volume located about this center point of the spherical target chamber.
TSF	Transport Spatial Filter. This is a pinhole located in the main NIF beamline.

Appendix B

Forward-propagating ARC laser characteristics

The first step in estimating the amount of counter-propagating light is to know the forward-propagating light. ARC was designed to have 1.5kJ in each incoming beam. Assuming a total beam area of 372mm square with a 20mm gap separating the beamlets, the average fluence in the forward-propagating light is 2.7J/cm^2. From there, the amount of 1w CP light can be estimated, assuming a 20% reflectivity from the plasma around the target. Assume a modulation factor of 4 (peak to average fluence) since the beam will not come back uniform for the ARC-short pulse. (For NIF, a standard modulation is about 1.3, so using 4 gives some margin.) For a long-pulse analysis (CV and ABE), the standard 1.3x modulation is assumed. ARC pulse widths are 1-50ps long.

	First order energetics calculations	Value	Unit
Nominal Drive parameters (forward propagation)	Energy per split beam	1500	J
	Flat-top split beam size	550	cm^2
	Average fluence at AM7	2.7	J/ cm^2
SWAG of Counter-Propagating light	SBS return fraction	0.2	
	Fluence reduction due to 2x angle	0.25	
	Average CP fluence at AM7	0.136	J/ cm^2
	Modulation factor	4	
	Peak CP fluence at AM7	0.545	J/ cm^2
Inputs to CP source model at DDS	Beam size reduction at DDS	0.77	
	Footprint reduction	0.59	
	Average CP fluence at DDS	0.231	J/ cm^2
	Peak CP fluence at DDS	0.925	J/ cm^2
Implications for ABE armor	Limiting aperture at AM7	39.0	cm
	Collimated energy in limiting aperture	207.4	J
	ARC throughput (ABE & CV & PV)	0.76	
	Collimated energy at AM1 input	157.6	J
Implications for ABE armor	Transport throughput (SF4 and SY mirrors)	0.93	
	Energy at TSF	145.8	J

Appendix C

Caveats list

Caveat	What we have now in the model	What could be wrong with that
Optics model uses simplified mechanical	Simple reps in all areas we thought were important	Something is missing
Tolerances	Optics have OCD positons and specifications (e.g. line spacing). Possible boresighting model fidelity errors	Installation, fabrication errors, or position errors (movement during vacuum), model fidelity
Bandwidth	None	In CV, more pointing deviation from gratings (fluence where previously none) FP: 1053.06 ± 2.5 nm CP: 1053.06 ±(2.5 + ?) nm
Polarization	Unpolarized source. Grating efficiencies are set to that for S-polarized. CV armor is set to S-polarized efficiency.	PV armor uses average of S and P reflectivity values, given AOI and index. Overestimates P and underestimates S reflection.
Source & mirror definitions	Testing extreme possibilities of mirror and source pointing, with poor sampling Ray sampling is 300x600 per beamlet	Something is missed
Halted rays	All metal halts rays. Sides of optics halt rays.	Scatter or grazing incidence from metal could send fluence elsewhere. Light enters side of grating
DDS shape	Deformed DDS models with 0.8-1.2mm P-V sag (Measured for un-mounted parts then adjusted for gravity vector)	LRU mounted figure error could be different. (Could cause caustics near AM5)
ΔX and ΔY rules	Determined for cases where $\Delta Z = 0$	Focus difference between beamlets causes diverging beam (high fluence light exiting aperture throughout entire beamline). Beam diverges slowly enough such that fluence decreases only 20% by TSF.

Appendix D

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